MOTOR TROUBLES

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MOTOR TROUBLES

THE TRACING OF DIRECT-CURRENT AND ALTERNATING-CURRENT MOTOR TROUBLES AND THE TESTING OF DIRECT-CURRENT AND ALTERNATING-CURRENT MACHINERY

BY

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PREFACE.

IN the following pages are given the methods that many years of experience have demonstrated to be simple and effective in the tracing and correcting of direct and alternating-current motor troubles. In addition are given the methods found best for direct and alternating-current generators and motors in order to find out completely their characteristics.

E. B. RAYMOND.

Schenectady, N. Y., 1907.

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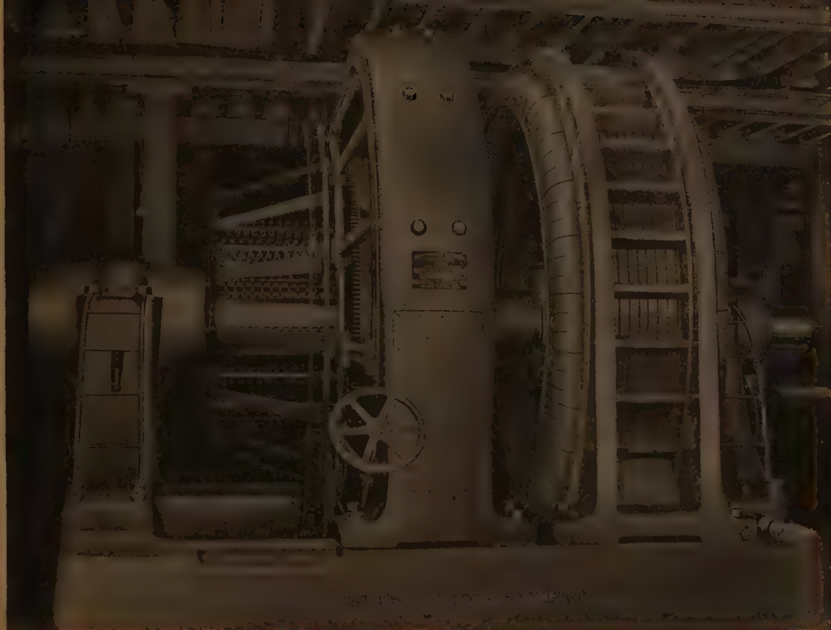
PART I.—THE TRACING OF DIRECT-CURRENT MOTOR TROUBLES AND THEIR REMEDIES.



GENERAL ELECTRIC CO.'S MOTOR GENERATOR SET.

CHAPTER I.—STARTING UP.

IT can generally be expected that apparatus purchased from an electrical manufacturing company will start up and operate without giving trouble, but circumstances may arise requiring undue straining, causing a weakening in certain parts, and perhaps necessitating an actual shutdown, with consequent loss and often with serious consequences. This weakening, though attended with immediate serious consequences, may not in itself be of great moment, and though at first sight the particular part causing the shutdown may not show its defect, there are certain well defined phenomena which indicate the exact cause and location of the trouble.

Such an investigation brought to an immediate issue is therefore most valuable, if the shutdown can be cut down to a small amount, avoiding the delay which would ensue in bringing an expert upon the scene. Further than this, such defects often show preliminary symptoms, which, if corrected at once, may be of small matter, but if allowed to run may be of much greater importance. Also an electrical apparatus is often purchased and sent to locations far away from the manufacturer, or even from expert advice.

Under such circumstances it is not only important that apparatus once running should not fail, but that it should be started up when first installed without undue delay and without calling for expert help.

CONNECTIONS AND ACTION OF SHUNT MOTORS.

The proper connections for a shunt motor are as shown in Fig. 1. The field *B* is connected as shown,

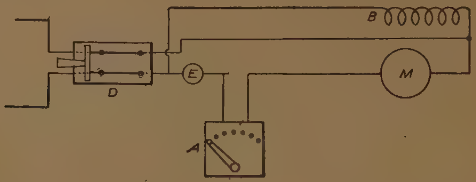


FIG. 1. CONNECTIONS OF SHUNT WOUND MOTOR.

so that when the switch *D* is closed it becomes excited before the armature circuit through the switch *E* is

FIG. 2. STURTEVANT TWO-POLE SHUNT-WOUND MOTOR.

closed. Thus, when the motor armature has current admitted to it through switch E and starting resistance box A, the field is already on, and thus the full torque of the motor is obtained; for the torque of a motor is equal to the product of flux per pole, the ampere turns on the armature, and the number of poles. Hence, if the full field is not on the motor at starting, full torque will not be obtained. Therefore, if a motor will not start when operating the starting-box and when current is flowing into the armature, an investigation should be made to see if the field flux is on, which can be done by holding a piece of iron, such as a key, against the pole-piece. If the flux is properly present the key will be drawn strongly against the pole-piece; if not, no attraction to speak of will be noticed.

REVERSED FIELD SPOOL CONNECTION.

There may be cases where the manufacturer has shipped a motor with one or more field spools reversed. If such is the case no torque, or, perhaps, very weak torque, will be noticed. Under such conditions a trial with a key will show proper field magnetism, yet the weakness or total absence of torque will be present, and a trial of polarity should be made.

TESTING POLARITY OF FIELD.

This can be done in two ways: First, by using a compass, bringing it near the various poles and noting the direction of the deflection of the needle. Since in all motors the poles alternate in magnetic polarity, in one pole the magnetism coming out and the next going in, it

follows that a certain end of a compass needle will point toward one pole and away from the next when matters are normal. If, however, two adjacent poles show similar magnetism, the trouble is located, and the offending spool should be reversed. This should be done *"end for end,"* not by turning on the axis. The latter operation does not change the direction of magnetism, while the former does. Direction of magnetism is determined by the following rule:

"Looking at the face of an electromagnet (such as the field spool of a motor), a pole will be north if the current is flowing around it in a direction opposite to the motion of the hands of a watch," Fig. 3, and south if in

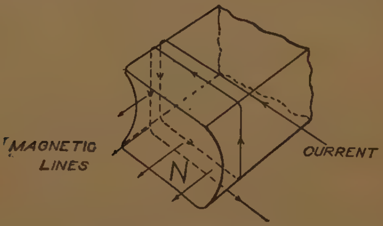


FIG. 3. DIRECTION OF CURRENT AND MAGNETISM IN POLE PIECE.

the same direction as the motion of the hands of a watch. It therefore can be seen that turning the spool upside down does not change the direction of the current around the iron core within the spool, and hence does not change the magnetism, but turning end for end accomplishes the result.

Another method of determining whether the magnetism of the poles is proper is to take two ordinary nails, the length depending upon the distance between pole-tips, being so chosen that the point of one nail can touch one pole-tip, the point of the other nail the other pole-tip, and the heads of the nails touching each other.

When the current is put into the field spools, the polarity between any two poles is properly related if the nails placed as suggested stick together by the magnetism. If there is no tendency to stick, the polarity of the two poles is alike and therefore wrong. The reason for this action is obvious. If the polarity is proper, that is, one pole south and the other north, the nails serve as a magnetic path, and hence an endeavor to separate them, owing to the magnetic attraction, requires force. If the adjacent poles are alike in polarity no magnetism passes through the nails, and hence no attraction exists.

OPEN FIELD CIRCUIT.

If, on closing the field switch, no magnetism is obtained by trial with a key, as suggested, there is an open circuit somewhere within some of the spools or in the wires leading to these spools. Under such conditions the open circuit must be found. It can be located by cutting out one spool at a time until the defective spool is discovered. On a two-pole motor try first one spool and then the other, as, for a very short time, say, 10 minutes, double voltage can be carried on a spool. On a four-pole motor and upward, three spools can always be left in circuit during the open circuit investigations.

LOW SPEED.

If the troubles suggested above do not exist, but the speed of the motor is too low or too high, the fault may be in the winding of the armature or field, in which case a remedy is a serious matter. On the other hand, considerable range of speed can be obtained by the choice of brush position on the commutator. Many motors will run without sparking with a range or brush shift on the commutator giving a range of speed of 15 per cent. Therefore, if the discrepancy of speed is within this amount, the brushes should be moved to counteract it, a backward shift of brush giving increased speed and a forward shift decreased speed. Any brush position, however, must be accompanied by practically an entire lack of sparking, since the latter trouble is a very serious matter, causing all sorts of trouble. A first-class motor should run at full load within 4 per cent (up or down) of the name-plate speed if the voltage is as called for on the name-plate. The speed at no load should not be more than 5 per cent higher than this, also the speed at full load, hot, should not be over 5 per cent greater than the speed at full load, cold.

C. & C. ELECTRIC CO.'S DIRECT-CURRENT MOTOR

CHAPTER II.—SPARKING.

A FIRST-CLASS motor should run without sparking, with the brushes fairly quiet on the commutator, and with a gloss on the commutator surface resulting from its operation. Sparking and roughening on the commutator may be due to poor design, in which case nothing can be done by the customer to make the operation satisfactory, but a very good motor for various reasons may give trouble from sparking.

ROUGH COMMUTATOR.

First, the commutator surface may not be perfectly smooth after receiving its last turn off. The work may have been poorly done by the manufacturer, with the result that the commutator surface, instead of being left smooth, is somewhat rough, Fig. 4. The result of this, especially with high-speed commutators, is that the brush does not make first-class contact with the commutator surface, that it may chatter with attending noise, and thus with many motors (especially the high voltage ones) the operation be attended with sparking. As a result, the commutator surface, instead of becoming bright and smooth with time, becomes rough and dull or raw in appearance, the brushes do not make good contact, and, hence, the heat generated even under proper commutator conditions, owing to the resistance of brush contact, is multiplied several times, with consequent in-

crease of temperature of the commutator. In addition the friction of brush contact (which should give a co-

FIG. 4. APPEARANCE OF ROUGH COMMUTATOR.

efficient of 0.2) is with a rough commutator much higher than it should be, which helps to increase the temperature.

HOT COMMUTATOR.

All this trouble is cumulative, so that the result finally is that the temperature will rise to a point where the solder in the commutator will melt, perhaps short circuiting or open circuiting the winding, with consequent inability to operate. A commutator will stand very slight sparking, but where it is noticeable and where it is continued for long periods of time, trouble, as indicated, is liable to result. Where, however, the load is

very light on a motor, quite a percentage of the time the full load or perhaps overload being on but little, a smoothing up occurs during the light period, which averts trouble. This is the reason that railway motors, though usually showing some sparking under their normal hour rating, give satisfaction as to commutation, the coasting of the car smoothing up the imperceptible damage done by the sparking during the heavy load.

LOOSE SEGMENTS.

A further and more serious cause of sparking and commutator trouble is due to the fact that the commutator may not be "settled" when shipped by the manufacturer. A commutator is made of many parts, insulated one from another, and all bound together by mechanical clamping arrangements. The segments themselves are held by a clamp on each end, which must be insulated from them and hold each segment individually from any movement relative to another.

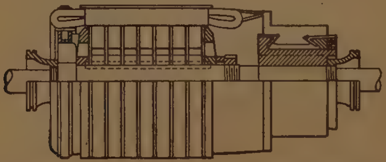


FIG. 5. SECTION OF COMMUTATOR AND METHOD OF HOLDING SEGMENTS.

Since the clamp must thus touch and hold down all segments, a failure to do so in any case results in a loose bar, which moving relatively to the next causes rough-

ness and thus sparking, with all its attendant accumulative troubles. The roughness of commutators due to poor turning or to poor design is shown uniformly over all the surface of the commutator on which brushes rest. A roughness due to a high or loose bar is shown by local trouble near the bad bar, and its corresponding bars around the commutator, the jump of the brush occurring there and being the cause of the sparking.

BLACKENING OF THE COMMUTATOR.

The sparking causes a local blackening instead of a uniform blackening, which occurs in case of poor design or poor commutator surface resulting from poor turning. Also, if the speed of the commutator is low enough, the spark will be noticed to occur at the time the bad segment passes the brush. At ordinary speeds, however, or where there are several loose bars, the sparking will not be different in appearance to that due to poor design or poor turning, so that an examination of the commutator surface must be made to place the cause.

It must be remembered that the very lightest movement of a bar, especially on the higher voltage and high commutator speed machines, may cause the trouble. A splendidly designed motor may show very poor operation, due to a commutator fault, as suggested.

CORRECTING ROUGHNESS.

The proper way to correct a rough surface due to poor turning is to grind the surface with a piece of ordinary grindstone, cut to convenient size to be held by the hand, and, if possible, rounded to the shape of the commutator, though the rounding is not absolutely neces-

THE BRYANT-BERY COMMUTATOR TRUING MACHINE.

sary, except when the surface is exceedingly bad. This grinding can be done without removing the brushes from the commutator and during the ordinary operation of the motor under load, Fig. 6, and thus does not in any way interrupt its work.

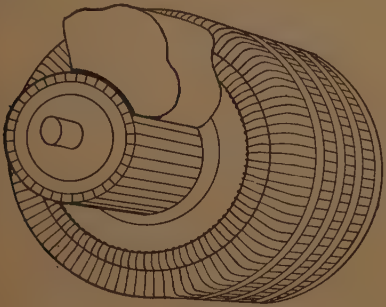


FIG. 6. GRINDING THE COMMUTATOR.

Where the sparking is due to poor turning, such grinding causes the sparking to entirely disappear. This is also a good method of cleaning the surface of brushes which have become coated with copper from the use of sandpaper in fitting them to the commutator surface.

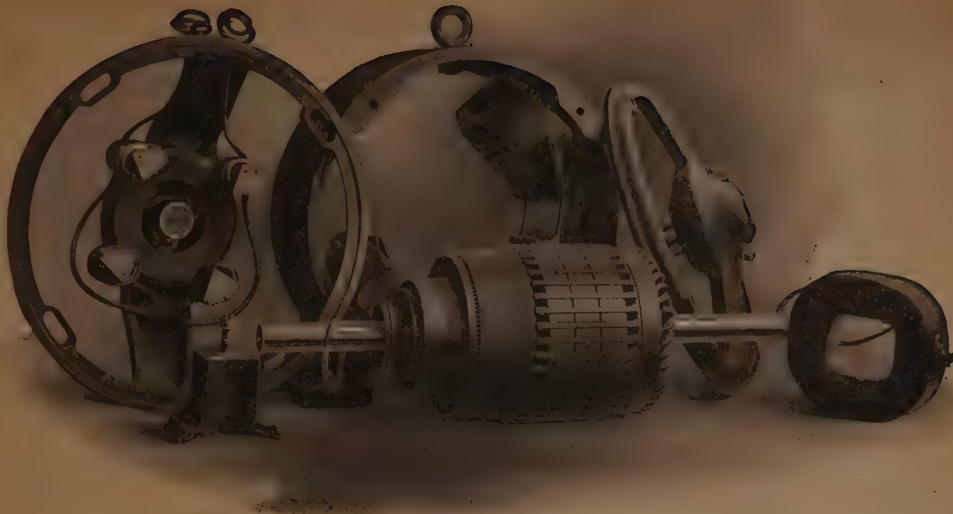
Some kinds of sandpaper, if used to give a brush surface or to smooth a commutator with the brushes down, imbed in the face of the brush hard material which sticks there, cutting the commutator, and thus collecting about itself copper from the commutator. An examination of the face of the brush after running a time will show these collections either in spots or all over the face

of the brush. The sand stone, used as suggested, removes all this.

Where, however, the roughness and sparking are due to a loose bar, grinding will do no particular good. Under such conditions a different process of correction must be followed. It consists first in getting the clamps which hold down the segments to touch and hold, each one preventing any relative movement of the bars, and after this is done, to get a smooth surface by turning, if the bar is much displaced, or by grinding if it is but slightly displaced. The process of correcting a loose commutator therefore appears as follows:

LOOSE COMMUTATOR CLAMP RINGS.

The first proposition is to get the clamps of the commutator down firm, so that when the commutator is at normal temperature no further screwing up on the clamping rings can be done without excessive effort. This is necessary in order that all the bars may have a direct pressure from the clamp, thus rendering any movement up or down impossible. The second proposition, after having gotten the clamps down, is to obtain a smooth surface. The method to follow to get the clamps down firm is to run the motor and, if roughness appears, shut down at a convenient time, and, while hot, tighten the clamping rings. If it is found that the tightening bolts can be screwed up somewhat, the machine should again be put in service for at least 4 hours, at the end of which time, if practical, shut it down again and make another trial on the tightening bolts. If, now, no more can be taken up on



WESTINGHOUSE MULTIPOLAR MOTOR AND PARTS.

the tightening bolts, a surface should be put on the commutator, either by turning with a tool or by grinding, if it is a mild case, and the machine once more put in operation. If the clamps have been got down as indicated and the surface of the commutator has been properly smoothed, satisfactory operation will result without further trouble.

OPEN ARMATURE CIRCUIT.

Another cause of sparking on a commutator is an open circuit in the winding, either in the armature body or, more often, where the lead from the armature winding is soldered to the commutator. In the latter case resoldering is an easy matter. If, however, the location of the open circuit cannot be found, the bars can be bridged over on the commutator itself by fastening with solder or otherwise, a strip of copper around the segments which indicate the break.

This indication is very apparent, for, if an open circuit exists, the long heavy spark which accompanies it promptly eats away the mica between the two segments which are each side of the break, and thus shows positively where to do the bridging over. Also an open circuit shows itself when the machine is running by the viciousness of the spark. It is unlike any other kind of commutator sparking, being heavy, long, and destructive in its action.

TESTS FOR OPEN CIRCUIT.

Another method of determining an open circuit in an armature is to apply to the commutator at two opposite points a low voltage, say from a battery or a dynamo

with its voltage kept low. Place an ammeter in circuit and clean the surface of the commutator bright and smooth.

Have the terminals leading the current into and out of the commutator small in cross-section where they touch the commutator, so that they rest only on a single segment, Fig. 7. Then note the current in the ammeter

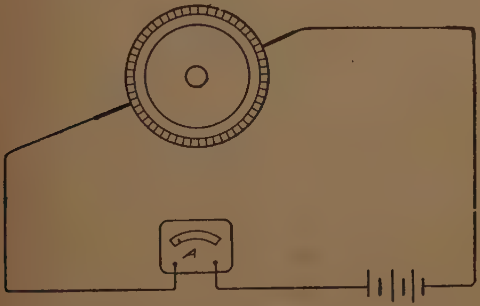


FIG. 7. CONNECTIONS FOR TESTING FOR OPEN CIRCUITS IN ARMATURES, WITH AN AMMETER.

and rotate the armature slowly. Where the open circuit exists the ammeter deflection will go to zero if the leads to the commutator bar have become entirely open-circuited, since the segment is attached to the winding through the commutator leads.

If the armature does not act exactly in this way try connecting a low-reading voltmeter or a galvanometer to two adjacent segments, while the current is passing through the armature as described from some external

source, such as a battery or a dynamo with its voltage held low, Fig. 8, and note the deflection. Pass from

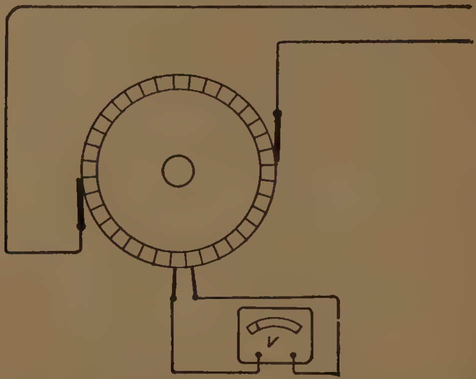


FIG. 8. TESTING FOR OPEN CIRCUITS WITH A VOLTMETER.

segment to segment in this manner, recording the drop between the successive pair of bars. This drop, if the current is held constant from the external source, should be the same between any pair of adjacent segments. If any pair shows a higher drop than the others near it, a higher resistance connection exists there, perhaps causing sparking and biting of commutator insulation, to a less degree, to be sure, than an actual open circuit, but enough, perhaps, to cause the trouble requiring the investigation.

TEST FOR ARMATURE SHORT CIRCUITS.

This last test is called a "bar to bar" test, and is most valuable in locating faults in armatures. It is the method

to use if a short circuit is suspected from one segment to another. When the part in which the short circuit or partial short circuit exists comes under the contacts, a low or perhaps no deflection is shown on the galvanometer or voltmeter, thus locating the defective place.

Such short circuits, if occurring when running, owing to defective insulation, burn out the coil short-circuited, since, when it passes through the active field in front of the pole-piece, an immense current is induced in it, causing a destruction of the insulation. When this occurs the coil should be open-circuited if the burning has not already accomplished it, and, if practical, be bridged over, as suggested.

REVERSED ARMATURE COIL.

Another trouble that may exist in an armature is a reversed coil. Instead of the armature winding progressing uniformly around from bar to bar of the commutator, at some point a coil may be connected in backwards. While manufacturers should weed out such mistakes, they do sometimes occur, causing annoyance, if not actual trouble, to a customer. Such a reversed coil often causes bad sparking, and an investigation should be made to determine its presence, if other remedies are not effective. A practical way is to pass through the armature at opposite points on the commutator a current, and then with a compass explore around the armature the direction of magnetism from slot to slot. If a coil is reversed when the compass comes before it, the needle will reverse, giving a very definite indication of the wrongly connected coil.

CHAPTER III.—BRUSH TROUBLES.

WHEN an excessive drop in speed from no load to full load is found, the position of the brushes on the commutator should first be investigated as has been previously discussed, always noting that no position should be chosen which causes sparking, with all its attending troubles, to appear,—in other words there is a nonsparking zone within which, depending upon the design of the motor, quite a range of speed can be obtained.

BRUSH RESISTANCE.

If this shows no relief the fit of the brush upon the commutator should be investigated, for any resistance in series with the armature causes a certain drop in speed, as the load comes on, the drop being larger almost directly in proportion to the size of the armature resistance.

Thus if in one case the resistance in series with a certain armature, plus the resistance of the armature itself were R and if in another case the resistance were R_1, the voltage upon the armature being E and the current I, the actual voltage which the revolutions of the armature must produce in the first place is $E = IR$, and in the second place $E = IR_1$. Thus if IR_1 is greater than IR the speed is less.

The resistance of surface contact of a carbon brush is a considerable factor, particularly with low voltage

TYPES OF BRUSH HOLDERS.
Crocker-Wheeler Co.
Allis-Chalmers Co.

TYPES OF BRUSH HOLDERS.
Ft. Wayne Electric Works.
Northern Electric Co.
General Electric Co.

and high current machines. This contact resistance is, at ordinary brush densities, about 0.028 ohm per square inch. The specific resistance of carbon itself is 0.002 ohms, hence, for an ordinary carbon, the contact resistance only is of consequence, the resistance to the passage of current through the carbon being negligible.

To illustrate this, an ordinary carbon brush runs at a current density of 35 amperes per square inch, so that the voltage drop for the whole machine is $2 \times 35 \times 0.028 = 1.96$ volts. The specific resistance is 0.002 ohm, giving a voltage drop through the carbon itself, assuming a length of brush of $1\frac{1}{2}$ inches, of 0.21 volt, which is negligible as compared with the drop of 2 volts from surface contact.

The surface loss of voltage is greatly increased if the fit of the brushes on the commutator is poor, due either to the cutting of grooves in the face by the use of coarse sandpaper, or to a part of the carbon actually not touching the commutator; hence when the drop of speed is excessive, this point must be carefully inspected. Finally, the spacing of the brushes must be checked. Poor spacing in some designs will not only produce a bad drop in speed but will reduce the efficiency and life of both brushes and commutator.

CHATTERING.

Another trouble sometimes experienced on direct-current motors is a noisy chattering of the carbons on the commutator. This effect under certain conditions, may become so prominent as not only to be of annoyance but actually to break the carbons. An examination

of the commutator will reveal no roughness, the surface being, perhaps, perfectly smooth and bright.

This trouble occurs principally with the type of brush holder which has a box guide for the carbon, the spring which forces the brush into contact resting on top of the carbon which has fairly free play in the box guide; also, the effect usually occurs with high-speed commutators, 4,000 to 5,000 feet per minute, peripheral speed.

Such brush holders are necessary on commutators which, like engine-driven machines, may run out of true on account of the shaft play in the bearings caused by the reciprocating motion of the engine. The clamped type of holder is usually free from bad chattering, but rocks on a commutator that runs out, causing poor contact and perhaps sparking.

The effect, therefore, when noticed, and occurring on a perfectly smooth commutator, seems at first a hard proposition to correct. Lubricating the commutator causes the chattering to immediately disappear but there is no commutator compound which gives a lubricating effect lasting over a half hour or so, and thus it is not practical to lubricate often enough to prevent the chattering. A sure remedy is to see that the angle of the brush with the radial line passing through the center of contact of the carbon and the center of the commutator is less than 10 degrees and that the carbon trails on the commutator instead of leads. Fig. 9 shows the setting which will stop all serious chattering and Figs. 10 and 11 show settings which may give trouble.

HIGH MICA.

Some motors under certain conditions roughen up their commutators after a short term of service, although no excessive sparking seems to be going on under, or at

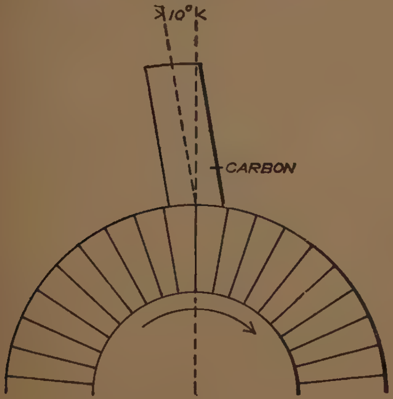


FIG. 9. CORRECT BRUSH SETTING.

the edges of the brushes. This effect may occur even though the commutator has been perfectly "settled," the method for doing which has been previously described. The commutator acts as if the mica used between bars to insulate the various segments, one from another, had protruded upward, causing the roughness noted and the resulting excessive sparking.

As a matter of fact, actual raising of the mica is a very rare occurrence, and, if it occurs, does so at certain spots and is easily identified. An

actual uniform protruding of mica, all over a commutator, as described, is practically an unknown phenomena. What actually does occur is an eating away of the copper surface of the commutator, leaving the mica between the bars high. A good machine will not spark enough to do this surface eating; a poor machine will.

The phenomena is easily identified, as the commutator surface looks raw all over instead of smooth and

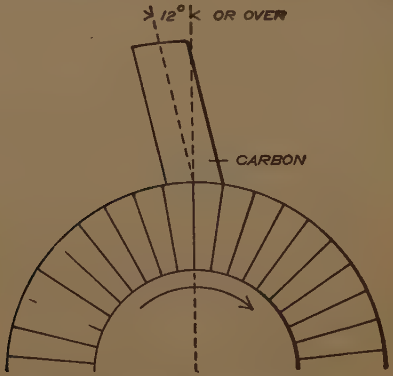


FIG. 10. BRUSH ANGLE TOO GREAT.

bright with a good brown gloss; if allowed to go too far, a general roughness appears, accompanied by sparking, until finally the sparking and heating will increase so much that the machine may flash over from brush to brush, blowing the fuses or opening the circuit breakers in the current. The trouble is much aggravated if the motor operates under load all the time. If it has

periods when the load is light, the commutator has a chance to be smoothed down by the brushes, so that the evil produced under full or overload is neutralized during the running under light load.

This fact is taken advantage of by railway motor designers. A railway motor coasts a considerable part

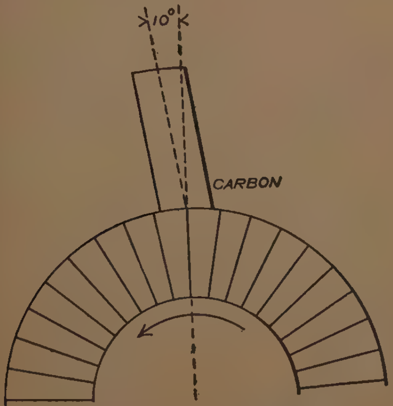


FIG. II. RUNNING IN THE WRONG DIRECTION.

of the time, during which period there is no current on it. Thus a smoothing process is taking place, neutralizing the roughening occurring under load. The railway designer purposely condenses his design, accepting sparking under heavy loads and thus getting large power into a small space,—a necessary quality in a railway motor.

For a roughened high mica commutator, in order to make matters satisfactory it is necessary; first, to place it on work where the load is somewhat intermittent; second, to replace it altogether; or third, to cut the

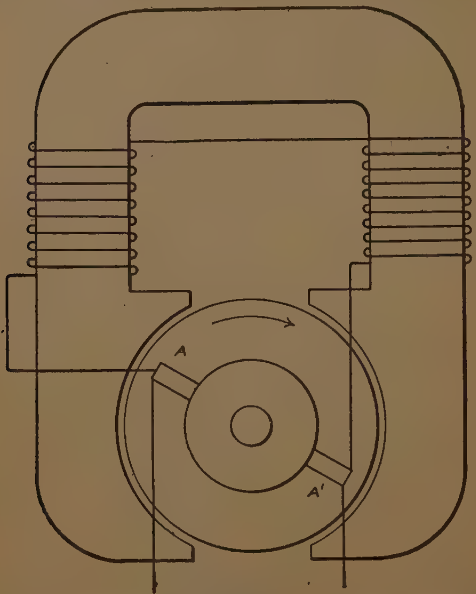


FIG. 12. CONNECTION FOR SHUNT-WOUND MOTOR, RIGHT HAND ROTATION.

mica between segments so that the mica surface is below the copper surface. Then, as there are no longer two different materials to wear down or to be acted upon

by the sparking, an unequal surface will not result. The mica need be cut down only 1/16-inch and a narrow, sharp chisel will do the work satisfactorily. No trouble will result from short-circuiting in this case, since centrifugal force keeps the slots clean. Some manufacturers of special apparatus ship the commutators thus cut out, as they realize the advantage thereby gained, and, in the case of mica trouble, the remedy is a most excellent one to try.

RUNNING IN THE WRONG DIRECTION.

Sometimes a motor when set up and started will run in a direction opposite to that desired. Under such circumstances the only change necessary is to reverse the field connection. Thus Fig. 12 shows the connection for one direction of rotation and Fig. 13 shows the connection for the reverse.

It should be noted that in Fig. 12 the brushes A and A^1 are shifted backward against the direction of rotation, so that, for the opposite rotation, a backward lead, as shown in Fig. 13, must also be chosen.

GLOWING AND PITTING OF CARBON BRUSHES.

Certain machines sometimes have a tendency to eat holes into the contact face of the carbon brushes on the commutator. This may be due to either of two causes, poor design or a wrong position of the brushes on the commutator. The error of design may be only in the choice of width of carbon brush used.

The design of direct-current apparatus, while brought to a splendid refinement, is not yet provided with a perfect working theory as to the exact width of

carbon brush to use on a given commutator. The area of carbon contact needed is well known, but the number of commutator segments which should be covered, that

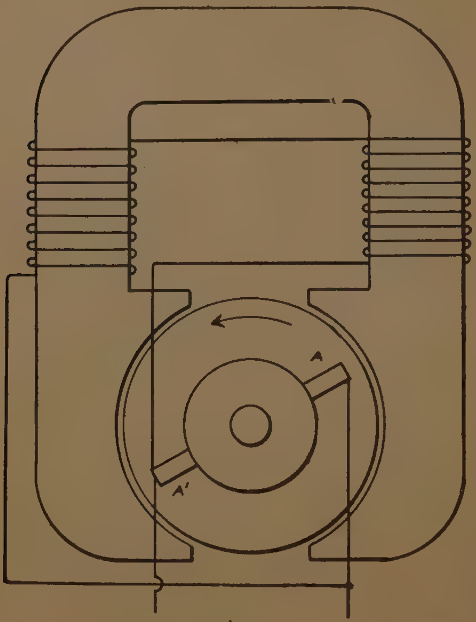


FIG. 13. SHUNT MOTOR CONNECTION FOR LEFT HAND ROTATION.

is the segment overlap, cannot be exactly predetermined, so that, if proper experimental data are not at hand or

a factory load trial is not given, trouble from both sparking and glowing will result if the width is chosen incorrectly.

The pitting referred to is due to glowing. If the glowing is at the edge of the carbon it is plainly visible and easily located. It may, however, occur underneath the carbon so that only by the most careful inspection can it be seen. Such glowing pits the carbon face by heat disintegration. With some machines three-fourths of the brush face may be eaten away and the pits be, perhaps, ¼-inch to ½-inch deep when discovered. A usual but incorrect decision is that the current per square inch of contact is too great, the calculation being made by dividing the current in the line by the square inches cross-section of positive or negative brushes. If this calculation shows a figure under 45 or 50, it is certain that the cause of the trouble has not been judged correctly.

The real cause of the glowing is, to be sure, excessive current through the carbon, but this is not the line current, if the calculation as stated, shows a brush face density below 50 amperes per square inch; it is a local current caused by the short-circuiting of two or more segments of the commutator by the brush resting upon them. The usual overlap of a carbon brush is about two segments, and while these two segments are under the brush, the armature coils connected to them are short circuited. If the design of the machine is such that the coil so short-circuited encloses stray flux from the pole tip, this flux will create in the short-circuited coil a current, perhaps many times larger than the brush is capable

of carrying, with the result that the glowing and pitting occurs.

PROCESS OF COMMUTATION.

The path of this current is as shown in Fig. 14. *A* is the carbon brush; *C, C′, C″* are the commutator seg-

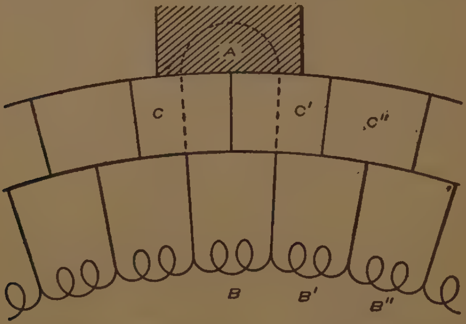


FIG. 14. SHORT CIRCUITING OF A COIL BY THE BRUSH WHEN COMMUTATING.

ments; *B, B′, B″* are the windings of the armature. At the position shown, coil *B* is short circuited by the carbon, the current passing into the face of the brush and out again as shown by the dotted line. This local current may be many times larger than the normal flow of current and is the one that does the pitting.

In true commutation, with no sparking or glowing there should be created in the short circuited coil under the brush, by means of the fringe or flux from the pole tip away from which the armature is revolving, an electromotive force just large enough to reverse the current

within the short-circuited coil and bring it up to a value equal to the current in the winding proper. Since on one side of the brush the current is in one direction and on the other side in the other direction, the act of commutation beneath the brush is to reverse this current and bring it up to the correct amount in the opposite direction.

With copper brushes this reversal of current has to be quite exactly done; with carbon brushes there is far less tendency to spark, so that they will stand a certain inexactness of commutation adjustment; in fact, experiments show that the carbon can resist as much as 3 volts creating current in the *wrong* direction and still not spark or glow, which is the property that has resulted in the use of carbon brushes instead of copper on most apparatus. When, however, this potential induced in the wrong direction, rises above 3 volts during the passage of the armature coil underneath the brush, trouble from sparking and glowing occurs.

This is why, in a motor, the brushes are pulled backward as far as possible at no load, so that the coil short circuited by the brush may enter the fringe of flux from the pole tip, thus creating the proper reversal of current during the time the coil is passing under the brush. Since adjacent poles are opposite in polarity, only one can give the flux direction proper for this reverse. In a motor it is always the pole backward against the direction of rotation from the brush and thus the brush requires a backward lead. In a generator it is the pole forward from the brush in the direction of rotation, hence generators require a forward lead.

If the motor gives trouble from glowing and pitting, the cause is probably this induced current, and the remedy is first to see if the lead of the brushes brings them in the most satisfactory place. If no change of lead can be found which will eliminate the trouble, the width of the brush must be changed. The wider the brush the longer does the coil suffer short circuit, as described.

On the other hand, the narrower the brush, the quicker must the current be reversed. There is, therefore, a width of brush which best satisfies both conditions.

Usually, however, where glowing occurs, the cause is too wide a brush, if the lead is found not to be responsible, and often serious trouble from this cause can be entirely eliminated by varying the width of the brush perhaps only ⅛-inch. I have known perfectly-designed machines to be entire failures in commutation, and by reducing the width of brush ⅛-inch made entirely O. K.

HOT ARMATURE COILS.

It may sometimes be noted that when a new machine is started up, local heating occurs in the armature, outlining by its action the exact shape of the armature coil. This may be due to the fact that, in receiving its final turning off the commutator was bridged over with copper from one segment to another by the action of the turning tool. An examination of the commutator surface will show this bridging over, which when removed, will cause entirely satisfactory operation of the machine, if the trouble has not gone too far and injured the insulation of the coil seriously.

PART II.—THE TRACING OF ALTERNATING-CURRENT MOTOR TROUBLES AND THEIR REMEDIES.

CHAPTER IV.—CHARACTERISTICS OF THE INDUCTION MOTOR.

WHILE the induction motor gives, in general, less trouble than the direct-current motor, faults develop occasionally that are exceedingly puzzling, causing annoying or, perhaps, serious delay. Before touching on the specific troubles sometimes met, it is necessary to call attention to certain characteristics of the induction motor.

It should be borne in mind that the induction motor at any given voltage has a limit to its output, which, if exceeded, results in the motor's stopping until the extra load is removed. The usual stationary induction motor is designed to carry, without danger of breaking down, 50 to 75 per cent over its rated load. For special purposes, this maximum output or breaking down point is from two to five times its rated output, depending upon the conditions to be met, but, the larger the maximum output in a given size of motor, the poorer is the efficiency, power factor, etc., at normal load. To get excellent all around results it is desirable to choose a reasonable value for the maximum output of the motor.

In an induction motor, the interesting characteristics to a purchaser, are:

1. Efficiency; that is, the ratio of the energy given out by the motor to the energy put in.

2. Maximum output, that is, the highest horsepower that the motor will carry without slowing down, unduly, in speed, or perhaps stopping altogether.

3. Current taken at the instant of starting, sometimes called impedance current. When the switch is thrown on an induction motor, there is a rush of current, that, on a poor motor outfit, causes disturbances of voltage on the line to which the motor is connected, thus giving occasion for complaints, especially if the circuit is supplying lights. If no lights are on the circuit, the disturbance may extend to other motors on the circuit, causing trouble with them.

4. Current taken when running without load. On an induction motor, the field is produced by a current drawn from the line through the same wires that supply the energy. This current, called the magnetizing or wattless current, lags behind the electromotive force, and pulls down the voltage of the circuit, from which it flows, to a much greater extent than an energy current, so that it is desirable to have as small a magnetizing current as possible.

On a well designed stationary motor for ordinary purposes, this no-load current should be not over 30 per cent of the total full-load current.

5. The power factor, which is the ratio of the component of the current, representing energy, to the total current flowing into the motor—the total current being the resultant of the energy current and the magnetizing current. Thus, in a motor taking 1,500 watts per phase (about 2 horsepower), at 100 volts per phase with a magnetizing current of 6 amperes per phase, the total

ALLIS-CHALMERS INDUCTION MOTOR.

current per phase flowing into the motor is found approximately, as follows:

$$\text{Total Current} = \sqrt{6^2 + \left(\frac{1,500}{100}\right)^2} = 16 \text{ amp.}$$

Let 1, 2, Fig. 15, equal the electromotive force applied to the phase; let 1, 5 represent, in direction and in length, the energy component of the current, and 1, 4

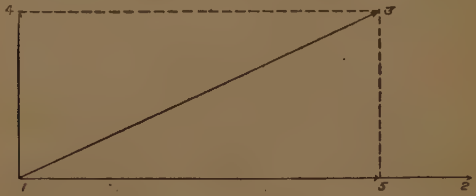


FIG. 15. PHASE RELATIONS OF ALTERNATING CURRENTS SHOWN BY THE PARALLELOGRAM OF FORCES.

the magnetizing current; then line 1, 3 represents the total current, or resultant of the currents, 1, 4 and 1, 5. This combination of currents is characteristic of alternating circuits. That is, currents combine directly only when in phase. When not in phase, they unite by the parallelogram of forces, as shown with 1, 4 and 1, 5 in Fig. 15. The power factor, therefore, is the ratio of the lines 1, 5 to 1, 3, or the ratio of the energy component of the current to the total current and this can be roughly estimated as shown.

CHAPTER V.—LOCATING FAULTS IN INDUCTION MOTORS.

SHUTDOWNS.

SOMETIMES, in the operation of induction motors there is trouble from blowing fuses, or possibly more serious trouble while the fuses do not blow and the motor, perhaps humming loudly, comes to a standstill. Under these conditions, the current may be ten times the normal amount, so that the heating effect, being increased one hundred fold, causes the machine to burn out its insulation.

Since the torque or turning power of an induction motor is proportional to the square of the applied voltage (one-half voltage produces only one-quarter torque) it can be seen that lowering the voltage has a positive effect upon the ability of the motor to carry load, and may be the cause of its stopping. Another cause for this trouble may be, that the load put upon the motor is more than the designed maximum output.

For some reason, the bearings may have become worn, so that the air gap, which, with everything normal, ordinarily is not much over 0.040 inch, and on small motors runs down to 0.015 inch, has been gradually reduced at the bottom to practically zero. Then, the point is soon reached where the armature commences to rub on the field. The friction soon becomes so great that the load represented by it, is more than the motor can carry, with the result that it shuts down.

Sometimes a shutdown may be due to hot bearings introducing an excess of friction, which, added to the regular load on the motor, gives a total load greater than the maximum output. Hot bearings, in turn, may be due to excess of belt tension, dirt in the oil, oil rings not turning, or improper line up of motor to its load; hence, under such conditions, it should be found out whether the voltage has been normal, whether the air gap is such that the armature is free from the field, and whether the load imposed upon the motor is more than that for which it was designed. In fact, in any installation of induction motors, it is well to have a system, where a regular inspector sees to the gap, bearings, etc., at stated times.

Shutting down may rarely be due to the working out of the starting switch, which is often located within the armature, and operated by a lever which engages a collar bearing contacts, which as they move inward, cut out the resistance in series with the armature and located within it. This resistance is used to keep down the current in starting, and is cut out, step by step, in some constructions by means of this lever. After it is all cut out, the motor counter-electromotive force takes the place of resistance, just as in direct-current motors.

If the short-circuiting brushes work back, introducing resistance into the armature while it is trying to carry load, it will at once slow down in speed and probably stop, usually burning out the starting resistance. Of course, this can occur only from faulty construction, and the remedy is to fit the brushes properly, so that they

PARTS OF A FORT WAYNE INDUCTION MOTOR, SQUIRREL CAGE TYPE.

will not work out. It is well to inspect them at the time of air gap inspection.

LOW TORQUE AT STARTING.

In attempting to start an induction motor, although the circuit to the motor is closed, it sometimes happens that no results are obtained. The same laws of voltage, etc., apply to the motor at starting, as when running, hence, the points under Shutdowns should be investigated and corrected, if necessary. The resistance, which is frequently inserted in the armature, may be short-circuited, thus giving a low starting torque, and, unless a starting compensator is used for starting, it is necessary, for obtaining a proper starting torque with a reasonable current, that a resistance be inserted. The resistance not only holds down the current, which would, ordinarily, be large, with the motor standing still, but it puts the current of the armature in better phase relation with the magnetism of the motor, so that, with the same current, a far larger torque is obtained.

It is necessary to have the mechanism for handling this resistance in good condition. The usual method of using it is to have brushes bearing on contacts revolving with the armature. As the motor starts, the brushes are moved forward, cutting out the resistance, the speed of rotation taking the place of resistance. A partial or complete short circuit of the resistance, therefore, partially or wholly ruins the starting torque.

LOW MAXIMUM OUTPUT.

It may be found that the maximum load, which a motor can carry, is less than desired, or less than the

name plate indicates. If the voltage, gap, load, etc., are all right, it may be possible that a mistake has been made in connections. Under such circumstances, it is easiest, naturally, to return the motor to the factory, but, if conditions are such that immediate operation is essential, the connections of the field can easily be changed so as to give a large increase in output.

To investigate what to do, remove the bracket on the side of the motor, covering the connections between the coils. Each motor has a certain number of poles. Pick out one phase, and find out how many groups of coils are connected up. From this, the number of poles can be determined. A better way is to calculate this from the speed of the motor and the frequency of the circuit on which it is running. Thus, the number of poles equals the frequency times 120, divided by revolutions per minute.

From an examination of the connections, it can be easily determined, whether the poles in any phase are connected in series or in multiple, or in series-multiple. Thus, in a motor, the connections may be as shown in Fig. 16, which shows the windings of one phase of a four-pole motor.

If the connections be changed to those in Fig. 17, each coil will then receive double its former voltage and the motor will give four times the output.

It should be borne in mind, however, that this makes the motor less efficient, increasing the exciting current, and thus lowering the power factor. If conditions demand it, this method may be followed. The temperature, under the new conditions should be carefully watched to

see that the extra magnetic flux and hysteresis resulting from the higher voltage on the coils, does not cause undue heating.

The only change in connections, that can be used for quarter-phase motors, is of the type of the one just described. On three-phase motors the poles can be grouped not only as previously suggested, but a variation of connections from delta to star, or the reverse, can be used. A delta connected, two-pole motor is shown in Fig. 18.

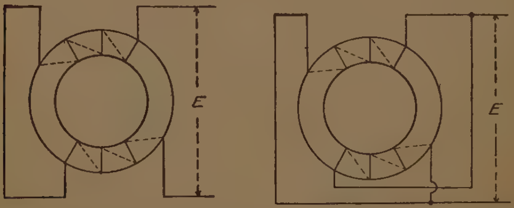


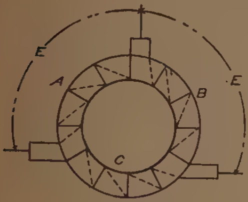
FIG. 16. INDUCTION MOTOR COILS CONNECTED IN SERIES.

FIG. 17. COILS CONNECTED IN SERIES-PARALLEL.

Where the three phases are indicated by the letters, *A*, *B* and *C*, any one of these phases may have poles in either series or multiple. In a delta connection with the coils spaced 120 degrees apart, as shown in Fig. 18, each phase has the line voltage *E*. In star connection, the phases are joined as in Fig. 19.

In this case, as in Fig. 18, each phase may have poles in series or in multiple. In the case of Fig. 19, each coil has a voltage of *E*, divided by the square root of three,

and on changing the connections from those of Fig. 19, to those of Fig. 18, three times the maximum output and capacity is obtained. Thus, by these two simple methods,



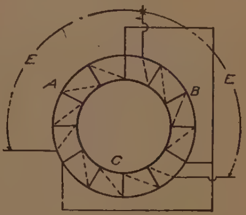


FIG. 18. DELTA CONNECTED COILS.

FIG. 19. STAR CONNECTED COILS.

a variation in any given motor of three or four times the output is available.

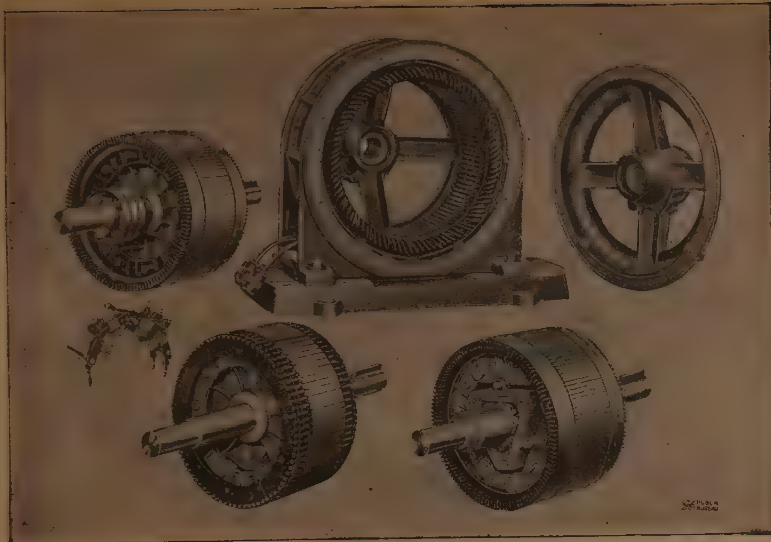
On a three-phase motor, by varying the pole grouping with star or delta connections, a smaller change takes place.

CHAPTER VI.—WINDING FAULTS.

WHEN a new induction motor is received, it sometimes happens that in attempting to operate the machine, it will start, the currents are excessive and unbalanced, undue heating appears, or a peculiar noise is emitted and accompanied possibly by dimming of the lights on the same circuit and the lowering of speed with perhaps actual shutdown of other induction motors thereon. If after examination, the air gap, belt tension, starting resistance and bearings are found O. K., the probabilities are that the motor has been wrongly connected at the factory of the manufacturer or the winding has received some damage during transportation. There are certain indications of this condition shown by various readings, so that, if far away from the factory, it may become important to locate the winding trouble and correct it. These faults may consist, in a three-phase motor, of:

1. One coil of the armature open circuited. The armature may have a defective winding just as does the field. This is the construction when a starting resistance is used. When a compensator is used and no starting resistance is required, the winding consists simply of bars connected at the ends by a ring.

2. Two coils or phases of the armature open-circuited.



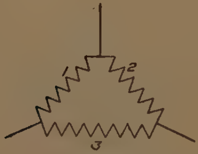
PARTS OF GENERAL ELECTRIC INDUCTION MOTOR.

3. Armature connected properly, field coil or phase reversed.

4. Part of field short-circuited.

5. One phase of field open-circuited.

Consider each case by itself, first with a delta-connected field. Actual readings on a 5-horsepower, six-pole, 1,200-revolution, 60-cycle motor under these conditions are given in the first table following.



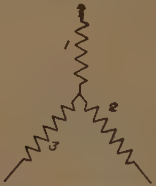


FIG. 20. DIAGRAM OF DELTA CONNECTED COILS.

FIG. 21. DIAGRAM OF STAR OR Y CONNECTION OF COILS.

Field delta connected as in Fig. 20. One coil or phase open-circuited. Running light with belt off motor, 220 volts applied, gave results as follows:

Volts between terminals.			Amperes on line.			Speed.
1-3	1-2	2-3	1	2	3	
220	220	220	27	27	27	615
		(Normal speed, 1,200.)				
		Motor armature stationary.				
220	216	216	6.2	19	13.2	Res. all in.
220	214	216	40	47	17	Res. all out.

From these readings it can be seen that the currents with the motor running were balanced and that the motor

only came up to about half speed instead of almost full speed, as it should. When standing still the currents were not balanced as they should be, but the armature tended to revolve and when allowed to turn slowly, the torque, or tendency to turn, varied slightly but not materially, or, in other words, the "dead points" were not particularly marked. In each case, leg 2 showed the proper current at standstill.

Actual readings on the same motor, delta connected field, two coils of armature open circuited and running free without belt, showed as follows:

Volts.			Amperes.			Speed.
1-3	1-2	2-3	1	2	3	593
220	220	220	6.8	6.8	6.7	Res. all out.
		Motor armature stationary.				
220	220	220	3.75	3.75	3.75	Res. all in.
220	218	214	27	32.1	6.27	Res. all out.

In this case the excitations were balanced. The motor would not start, as it should, at any point with the starting resistance in circuit. With the resistance cut out, the motor started at certain positions with a jerky motion for a few revolutions.

The test with the armature stationary showed the amperes in the different legs to be balanced with the resistance all in, but in each case low, amounting to but 20 per cent of the current obtained under normal conditions.

Actual readings on the same motor delta connected, armature connected correctly, one coil or phase of field reversed, excitation normal.

Volts.			Amperes.			Speed.
1-3	1-2	2-3	1	2	3	
220	220	220	3.45	3.45	3.45	1,194

With phase 1 reversed, the direction of rotation reversed, the motor came up to only 700 revolutions with all the starting resistance in the armature circuit. When the armature resistance was short circuited, the speed dropped rapidly.

Armature blocked, correct connection.

Volts.			Amperes.			Resistance.
220	220	220	20	20	20	Res. all in.
220	220	220	43.5	43.5	43.5	Res. all out.

Armature blocked, phase 1 reversed.

220	220	220	37	19	18	Res. all in.
220	220	220	47	50	43	Res. all out.

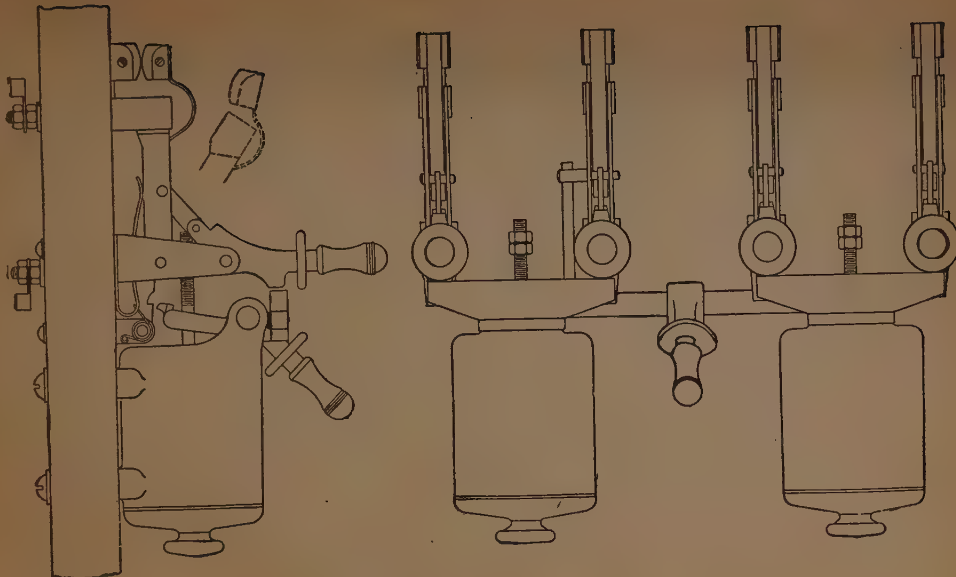
With the proper connection, dead points were noticeable at starting, but not to any marked degree, the starting resistance being cut out. The currents were all alike, as they should be, in the three branches. With one phase reversed and the resistance cut out, the dead points, or points of no particular torque, and maximum torque points, were so decided that the armature was with great difficulty pulled from one dead point to another by means of a lever on the pulley. The currents showed greater unbalancing with the resistance in than out.

With the armature removed from the field, the readings of current into the motor were:

Volts.			Amperes.		
220	220	220	43	43	43

STARTING BOX FOR INDUCTION MOTOR.
Crocker-Wheeler Co.

STARTING BOXES FOR INDUCTION MOTORS.
Allis-Chalmers Co.



STARTING BOXES FOR INDUCTION MOTORS.
General Electric Co.

Reading with phase 1 reversed.

212	221	220	72.5	45.2	79

Thus with the motor connected properly, the current was about 90 per cent of the current under normal conditions with the armature in and the resistance short circuited, and, with phase 1 reversed, the current became greatly out of balance.

All the previous readings were as follows, when this same motor was Y connected, as in Fig. 21, instead of delta. With one coil or phase of armature open circuited, running light with 220 volts applied, the following readings were obtained:

Volts.			Amperes.			Speed.
1-3	1-2	2-3	1	2	3	
220	220	220	1.8	1.8	1.8	590; Res. all in.
220	220	220	7	7	7	599; Res. all out.
						(Normal speed 1,200)
Motor armature stationary.						
220	220	220	6.6	4.2	2.7	Res. all in.
220	220	220	15.5	10	7	Res. all out.

When running light, the motor behaved as when connected delta under similar conditions. When standing still, one leg took the proper current; the other two, 65 per cent and 45 per cent of the current instead of all taking the proper current alike.

Actual readings on the same motor Y connected, two coils of armature open circuited, with motor running free without belt and resistance all cut out, showed as follows:

Volts.			Amperes.			Speed.
220	220	220	1.7	1.7	1.7	590

With starting resistance all in, the motor would not start, and with the starting resistance out, the motor started only at certain points.

Armature stationary.

Volts.			Amperes.			Resistance
220	220	220	1.25	1.25	1.24	Res. all in.
220	220	219	7	1.76	8.3	Res. all out.

As in the case of the delta connection, the currents are balanced with the resistance all in, but in each case less than under normal connection, and, with the resistance cut out, the current is unbalanced badly, instead of being alike as in the proper connection.

Readings with armature connected correctly, one phase of field reversed, excitation normal connections were:

Volts.			Amperes.			Speed.
1-3	1-2	2-3	1	2	3	
220	220	220	1.37	1.37	1.37	1,186
			Phase 1 reversed.			
218	216	220	10.2	6.7	3.5	1,160

Motor came up to speed without extraordinary effort when the short-circuiting switch was thrown in, but the currents were unbalanced.

Armature blocked, correct connection.

Volts.			Amperes.			Resistance.
220	220	220	6.5	6.5	6.5	Res. all in.
220	220	220	16.3	16.2	16.3	Res. all out.

GENERAL ELECTRIC SINGLE-PHASE INDUCTION MOTOR.

Armature blocked, phase reversed.

220	220	220	8.9	9.4	4.03	Res. all in.
220	220	220	18	17.6	17.6	Res. all out.

Very decided dead points and points of maximum torque were obtained. From the tables it is seen that reversing the phase, throws the currents out of balance, both running free and with the armature blocked.

Armature taken out, normal connection.

Volts.			Amperes.		
1-3	1-2	2-3	1	2	3
220	220	220	14.7	14.7	14.7
Phase 1 reversed					
217	218	220	26.2	16.8	19

With the field properly connected, the current is 14.7 amperes on 90 per cent of the current under the same conditions with the armature in the frame. With the phase reversed, one leg takes about normal current, the other two currents are much larger.

OPEN CIRCUIT IN FIELD.

Under these conditions in a three-phase motor, the current would only read in two legs. The other leg would not read and the motor would not start from rest with all switches closed. It should be borne in mind, however, that a three-phase motor or a quarter-phase motor will run and do work single-phase if it is assisted in its starting. The starting torque is zero, but as the speed increases the torque increases.

On a small motor, even giving it a start with the belt will introduce enough torque to the motor so that it will

pick up its load. Thus, while an open circuit in the field winding should be found and repaired, if there is not time to do it, the motor can be operated single-phase to about two-thirds of normal load. The power factor conditions and the effect on the rest of the circuit is practically no worse than on three-phase. The torque of a 1-horsepower, three-phase, induction motor from rest to synchronism, when running single phase, is shown in Fig. 22; the torque curve of a 20-horsepower, three-

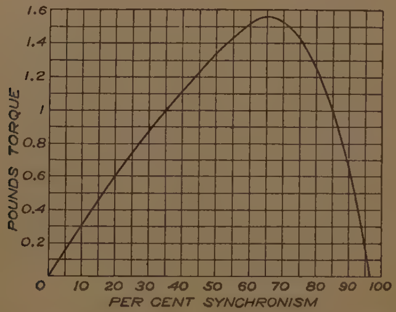


FIG. 22. TORQUE CURVE OF A 1-HORSEPOWER, THREE-PHASE INDUCTION MOTOR RUNNING SINGLE PHASE

phase motor in Fig. 23, and of a 1-horsepower, three-phase in Fig. 24.

Fig. 25 shows the power factor, commercial efficiency and the apparent efficiency of a 20-horsepower, three-phase motor, and Fig. 26 the same single phase. Apparent efficiency is the ratio of the actual output and the apparent input. The apparent input is greater than the

actual input, due to the input current carrying with it the magnetizing current. The ratio between these various

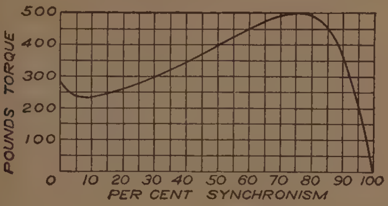


FIG. 23. TORQUE OF A 20-HORSEPOWER THREE-PHASE INDUCTION MOTOR.

quantities is shown by the equation: Real input equals apparent input times power factor.

In Fig. 22 it will be noted that the torque of the

FIG. 24. TORQUE OF A 1-HORSEPOWER THREE-PHASE INDUCTION MOTOR.

motor at starting is zero, rising to a maximum and reaching zero at synchronism. This means that an induction

motor never runs at full speed, but to produce torque drops off a few per cent (in a first class motor about 2 or 3 per cent) before operating torque is obtained. The three-phase motor starts with a reasonable torque, reaches its maximum output and goes to zero again at synchronism.

Figs. 23 and 24 show the torque curves started without resistance in the armature. With resistance inserted in the armature, the torque is greater at starting and less later, which is the reason that it is advantageous to intro-

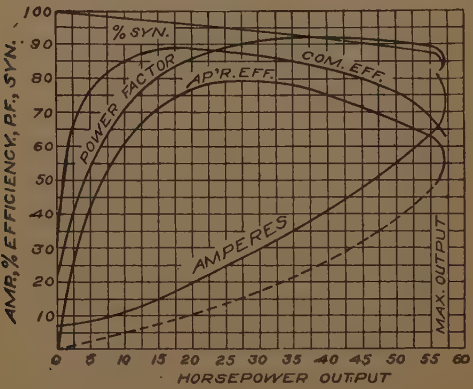


FIG. 25. EFFICIENCY AND CURRENT CURVES OF A 20-HORSEPOWER THREE-PHASE INDUCTION MOTOR.

duce resistance at starting and cut it out as synchronism is approached.

In looking at Figs. 25 and 26, it will be noted that the

power factor starts at zero, when the motor is going at no load, rises to a maximum and then reduces. Also the motor reaches a certain output beyond which no further

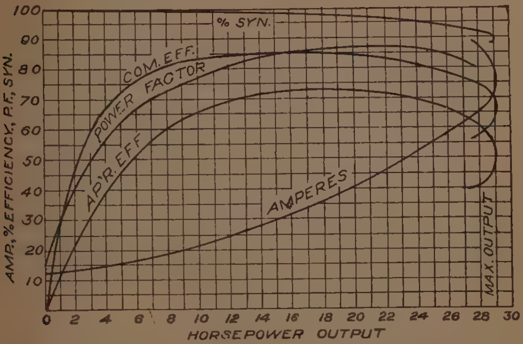


FIG. 26. CURVES OF MOTOR OF FIG. 25 WHEN RUNNING SINGLE PHASE.

load can be taken, the commercial and apparent efficiency dropping off and reaching zero, when the motor stops. This illustrates the point brought out previously, that the stopping of an induction motor may be due simply to too much load.

Thus, by taking the simple readings as shown previously a diagnosis of the winding condition can be determined and a correction applied, perhaps saving much of the delay entailed by obtaining a new motor.

Fig. 27 illustrates the torque curves of an induction motor from rest to synchronism, running both three-phase and single-phase with resistance and without re-

sistance. Curve *A* shows the torque from rest to synchronism without resistance. If resistance is inserted curve *B* is obtained and the starting torque is 440 pounds against 170 without resistance. Curve *C* illustrates the torque where there is too much resistance used, 0.0833 in the rotor; curve *F* illustrates the torque single phase, being zero at starting An induction motor starts on

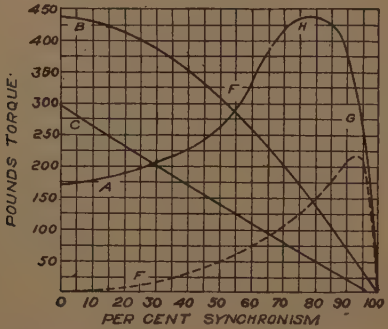


FIG. 27. TORQUE CURVES OF A 30-HORSEPOWER INDUCTION MOTOR.

curve *B* until it reaches the point *F*, when the resistance is cut out and the motor adjusts itself to its operating position at *G*. Thus, if the torque in this particular motor is greater than 440 pounds, shown at *H*, the motor will break down and come to rest. With the resistance of 0.0388 in the rotor a starting torque of 440 pounds is available, but it will not bring this load up to normal speed. It will only bring the load represented by the

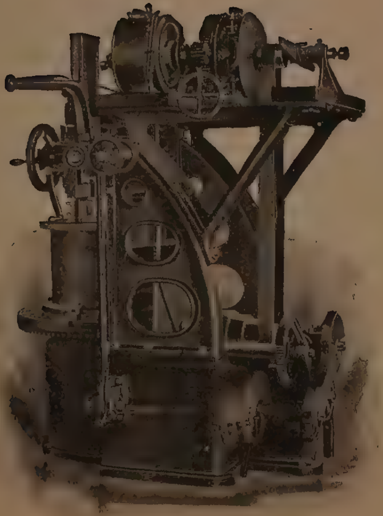
point F up to normal speed; in other words, 290 pounds. These curves graphically indicate the variation of power in an induction motor from rest to synchronism, with and without resistance.

CHAPTER VII.—BALKING OF INDUCTION MOTORS.

FOR a three-phase induction motor the torque has been shown in Chapter VI, p. 70, Fig. 27, and it has been noted that the torque (or turning power) has a certain value when the motor is at rest; and that the curve rises with even gradations to a maximum and then reaches zero at synchronism. This is the normal curve and the motor will start and bring to synchronism its proper load without interruption.

There may be, however, some peculiar actions in squirrel cage motors with certain slot relations between armature and field, whereby at one certain percentage of speed the torque will go almost to zero. Thus, the motor will start its load properly, but will suddenly lose its torque at some slow speed, perhaps one-tenth. Such motors might be installed and give satisfaction for a while, but, as the customer's requirements increased and the motor had load added to it from time to time, a day might arrive when, for some unknown reason, the motor would stop at, say, one-tenth speed; all usual investigations might be made and nothing found wrong.

Such trouble may be caused by a magnetic locking effect of the teeth of the armature with the poles of the field. I have seen a motor with six poles and sixty slots, drop its torque at one-tenth speed to one-fifth of its proper value. This phenomenon, with ordinary measuring instruments and testing facilities existing under usual



FORT WAYNE INDUCTION MOTOR DRIVING A BORING MILL.

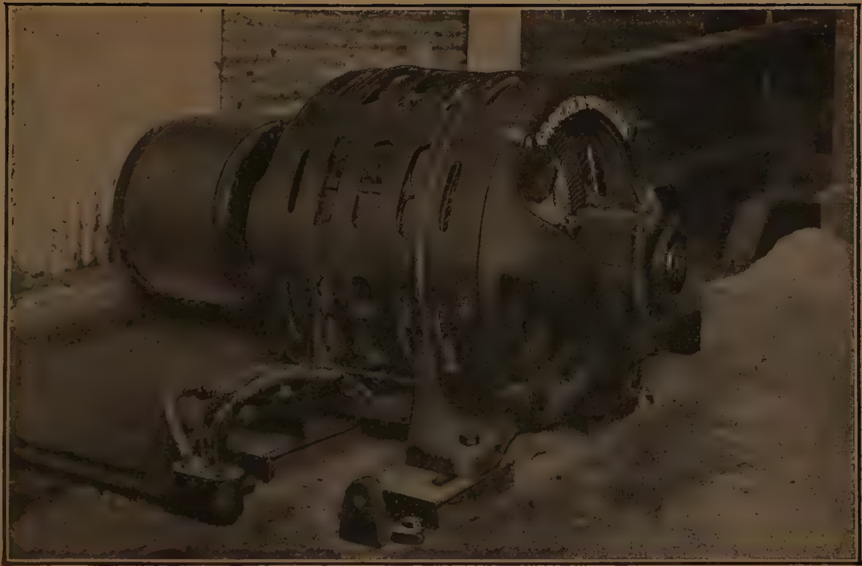
conditions, cannot easily be measured; but by special torque measuring instruments the peculiar synchronous locking can be measured and exactly located. If all other investigations show no cause of weak torque during the rise of the motor from rest to synchronism, the relation between the number of poles and slots in the rotor may account for the trouble. This is an unusual case but on squirrel cage motors it *has* existed; it is, therefore, mentioned here. There is no remedy but to change the design, so that the manufacturer must take action for correction.

SQUIRREL CAGE ARMATURE TROUBLES.

Peculiar actions such as heretofore discussed on poor operating with dead points, etc., due to reversals of phase, phases open-circuited, and other causes, occur with squirrel cage armatures as well as with definitely wound armatures when the manufacturer has done poor soldering on some of the connections of the armature bars. Sometimes such a solder flux may be used, that while proper action may occur for a while, time develops, at certain points, weakness of electrical contact due to chemical action starting up at the joint. Thus, while in the factory test the motor shows up O. K., on the customer's premises, after a time, poor operation results; so that actions which have been outlined with open circuits in armatures, when the armature has a regular progressive winding, may occur with squirrel cage armatures when improper soldering has been done.

If the resistances of the squirrel cage joints are all uniformly high, the action is simply like an armature

ALLIS-CHALMERS INDUCTION MOTOR FAN OUTFIT.



A CROCKER-WHEELER INDUCTION MOTOR.

with a permanent resistance inserted, which results simply in a lowering of the speed and a local heating at the joints. If some of the joints are all right, but some are bad, then the unbalanced effects mentioned appear with the ability to come up to speed possibly destroyed and with unbalanced currents and other indications of abnormal action.

EFFECTS OF UNBALANCED VOLTAGES.

In an induction motor the maximum output can be seriously affected by the fact that the voltages applied to the motor are not equal in amount. On a three-phase system, the three voltages between the legs 1-2, 2-3 and 1-3 should be approximately equal; also on a two-phase system, the voltages 1-2 and 3-4. If these voltages, as delivered to the induction motor, are not alike, but more or less apart from each other, the maximum output of the motor is proportionately affected, as well as the current in the various legs.

For instance, on a two-phase motor, if the voltages differ in the two legs by 20 per cent, which is a condition sometimes met with in normal practice, the output of the motor may be reduced 25 per cent, so that, instead of giving its maximum output of, say, 50 per cent for a few moments, it will be reduced to 12 per cent, and thus the varying loads which the motor may have to carry may shut it down. In the case of low maximum output, the relative voltages on the various legs should always be read and if they vary as above, the trouble may be due to this.

In addition to the effect on the maximum output, the

poor distribution of current in a two-phase motor under such conditions may be quite serious. Take a specific case of a 15-horsepower, six-pole, 1,200-revolution, 220-volt motor, with the voltage on one leg 220 and the voltage on the other leg 180; current in leg No. 1 was 60 amperes and in leg No. 2, 35 amperes at full load. The normal current at full load was 35 amperes. Thus, the fuse might have blown in the circuit carrying the high current, causing the motor to run single-phase. If, when an attempt was made to start the motor next time, it were not noticed that the fuse was gone, no starting torque would exist.

Take the specific case of a six-pole, 10-horsepower, 1,200-revolution, 160-volt, three-phase motor. This motor on normal voltage at full load took 110 amperes in each leg. With an unbalancing of voltage of 161, 196 and 168, only full load could be carried, although the average of these voltages is such that 25 per cent overload should be carried.

STARTING COMPENSATOR TROUBLES.

Some induction motors of the squirrel cage type are started with compensators. These are connected to the motor, reducing the line voltage on the system to a lower voltage at the motor, Fig. 28. When the motor has started and is turning freely, a switch is thrown so that the full voltage is put upon the motor. Since the current required at starting has a certain value when a compensator is used, the current drawn from the line is reduced by the ratio of the compensator reduction. Thus, if the compensator has a ratio of 1 to 2, and the field voltage is

100 on the line and 50 on the motor at starting, and the motor takes 50 amperes, only 25 amperes would be drawn from the line and thus the motor at starting would have less effect on other apparatus connected with that

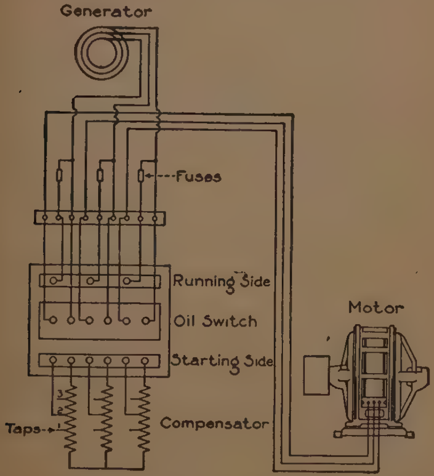


FIG. 28. CONNECTIONS OF STARTING COMPENSATOR FOR INDUCTION MOTOR.

line. This compensator is the method of starting in general use on squirrel cage motors.

Sometimes a mistake in connection is made on the compensator so that full voltage is used at starting and the lesser voltage after throwing over the switch. Thus, the motor at starting takes excessive current, and, since

the maximum output is in proportion to the square of the voltage, the motor capacity is much reduced when it is apparently running on the operating position. Such action, therefore, can usually be accounted for by a wrong connection in the compensator. Sometimes a motor connected to a compensator takes more current at starting than it should, under which conditions a lower tap should be tried. Compensators are usually supplied with various taps and the one should be chosen which produces the least disturbance on the line, giving at the same time the desired starting torque on the motor.

When a motor will not start, having been connected to a compensator, the cause may be entirely in the compensator. The compensator may have become open-circuited, due to a flash within. The compensator switch may have become deranged, so that it will not close, or, a connection within the compensator may have become loosened. Possibly when a motor will not start when connected to a compensator just put into use, a secondary coil may be "bucked" against another secondary coil within the compensator so that no voltage is produced by the compensator at the motor. This results in no particular heating and no apparent phenomenon which would account for the motor not starting. An ammeter in the motor leads would, naturally, show the absence of current, or a voltmeter would show the absence of voltage between the lines.

CHAPTER VIII.—MECHANICAL TROUBLES.

COLLECTOR RING TROUBLES.

SOME induction motor armatures are provided with collector rings upon which rest brushes from which wires run to the starting resistance located outside of the motor proper. Foreign manufacturers use this method of motor starting freely and it is used somewhat in the United States. Under these conditions, it is essential that the contact of the brushes upon the collector rings be in good shape, else the contact resistance at this point will be so large as to slow the motor down and to cause heating of the collector itself.

This effect is particularly noticeable when carbon brushes are used. The contact resistance of a carbon brush under normal operating pressure and carrying its usual density of current (40 amperes per square inch) is 0.04 ohm per square inch. Thus, under normal conditions, the drop is 0.04×40, which equals 1.6 volts. If the contact is only one-quarter the surface, this drop would be 6.4 volts, and might materially affect the speed of the motor. Thus, if on such a type of motor, the speed is below the synchronizing speed more than it should be (normally not over 4 per cent), an investigation of the fit of the brush upon the collector may show up the trouble.

If copper brushes are used, this trouble is much less liable to occur, since the drop of voltage, due to contact

resistance when running at normal density (150 amperes per square inch), is only one tenth that of carbon. The same trouble may occur due to the pigtail, which is usu-

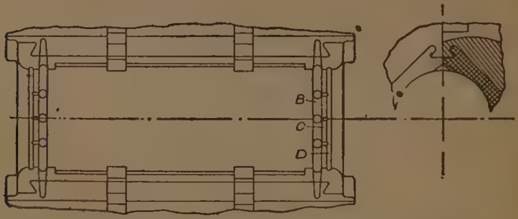


FIG. 29. GROOVES TO CATCH OIL LEAKAGE.

ally used with carbon brushes, making poor contact with the carbon, which gives the same effect as a poor contact with the collector itself.

HUNTING.

It is universally accepted as a fact that the induction motor runs at a constant speed, that is, there is no surging up and down in speed, an effect which has received the name of "hunting." It is a fact, however, that in very rare circumstances an induction motor will hunt just like a synchronous motor. In the latter the hunting tendency is very common and has to be met by special applications and guarded against in design A hunting induction motor, while rare, is disastrous as far as operation goes. The phenomenon appears in the form of a speed variation 1 or 2 per cent each side of the normal speed, swinging from one side to the other, taking up a

period of vibration depending upon the conditions. It may be anywhere from 10 to 500 swings a minute.

This rare phenomenon of induction motors depends upon the drop in the line between the generator operating the induction motor and the motor itself, and upon the design and slot relations of field and armature. The trouble is rare, but when it occurs it is very serious. It will stop if the line resistance be cut out between the motor and the generator. If this is not possible, it can sometimes be stopped on a three-phase motor by changing from delta to Y connection, or possibly the grouping of the poles may be changed In any case, the flux in the motor is altered.

The period of this hunting has nothing whatever to do with any hunting of the generator, and hunting of the motor may occur when even though the generator speed is exactly uniform. This action is entirely distinct from a variation of the uniformity of the speed of the generator due to the engine driving, which lack of uniformity is repeated by the motor itself. It is more vicious and usually results in a gradual increase of amplitude of swing until the motor finally gets swinging so badly that it finally breaks down and stops entirely. Ordinarily, the manufacturer is responsible, but a change of connections will often clean up the trouble and thus keep the apparatus in operation until a permanent arrangement can be put into effect.

IMPROPER END PLAY.

Induction motors are designed so that the revolving parts will play endwise in the bearings 1-16 inch or so. In order to accomplish this, the center line of the rotor

must coincide with the center line of the stator. If in setting up the machine the limits in this end action of the bearings are such that these center lines are displaced sideways, there is then a strong magnetic pull tending to bring the center lines together. If the bearings will not permit the center lines to get together, the thrust collars will have to take the extra thrust and, in an induction motor, this force is very considerable.

If on top of this magnetic thrust the belt pull is such as also to draw in the same direction, this trouble is increased. As a matter of fact the end force may be such as to get the bearing excessively hot and to actually cut into it, rendering the motor inoperative before a great while.

In the case of trouble with bearings, the end play should be investigated. It can be tested by pushing against the shaft with a small piece of wood, using the shaft center for the purpose. With the machine operating under normal conditions there should be no particular difficulty in pushing the shaft first one way from one side, and then the other way from the other side. It is found that the revolving part is hugging closely against one side, the pressure causing it may easily reach a value that would heat the bearing excessively. The trouble can be corrected either by pressing the spider along the shaft in a direction towards which the hugging is occurring, or by driving the laminations of the rotor in the same direction. The part of the laminations to choose to drive should be the tops of the teeth. It will be found that, with a wooden wedge, the tops of the teeth can be driven over without any difficulty in ordinary designs,

⅛ to 3-16 inch. This amount of movement will usually correct the trouble. Driving the teeth of the stator in the opposite direction to that of the end thrust ⅛ inch or so will usually accomplish the same result. It is best to choose the teeth (stator or rotor) which are most easily driven over, the thin long ones moving easier than the short broad ones.

BALANCE.

Improper balance may be due to a sprung shaft or to an actual unbalanced condition of the rotating parts. If this trouble occurs, the revolving parts should be taken out and put into a lathe, to see whether the shaft is true and then put on balancing ways to check the balance. Shafts are sprung with surprising ease. Treatment that one might expect would cause no trouble, may throw a shaft out an amount sufficient to cause vibration in operation, particularly with the higher speeds to which manufacturers are going in apparatus.

In the case of very high speeds (1,800 revolutions or over), ordinary static balance, even if carried out most effectually, may not correct balance trouble, the reason being that the static balance and the dynamic balance are two entirely different things. If, for instance, the trouble of balance is caused by the structure being out on the revolving part, say on the right-hand side, in balancing statically, the weight might be placed on the left-hand side and, as a result, at high revolutions there would be a twisting effect causing vibration.

To truly correct the trouble for such high speeds, the balancing weight should be placed opposite the part of

the structure which is causing the trouble. If after having statically balanced a rotor the vibration still continues, the same balancing weight should be moved to the other end of the revolving element, which will often correct the trouble. If this does not do it, there will be noticed a change for better or worse and, by trial, a point longitudinally along the rotor will be found where the balancing weight will correct the vibration.

OIL LEAKING.

Sometimes the bearing of a motor will permit the oil within to be drawn out, perhaps a very little at a time, accumulating enough after a few days or a few weeks to show on the outside or on the windings of the machine. While a motor will run for some time wet in its windings with ordinary lubricating oil without being apparently injured, it is a fact that insulation soaked with oil in this fashion will deteriorate and eventually give out. It, therefore, becomes important to stop the leak.

One of the principal causes is a suction of the oil due to the drafts of air from the rotor, and one of the best methods to stop the trouble, under ordinary conditions, is to put in grooves as shown in Fig. 29 at *B* and *D*. These grooves on a 50-horsepower motor may be ⅛ inch deep and 3-16 inch wide, having three holes drilled through the bearing shell to take the oil which is collected by the grooves back into the oil well. These grooves are just as effective with the split as with the solid bearing. It is impossible here to go into all the various causes of oil leakage. The grooves as suggested are a general remedy and cover many cases.

CHAPTER IX.—TROUBLES WITH SYNCHRONOUS MOTORS.

IN GENERAL, a synchronous motor is an alternating-current generator used to take in current instead of giving it out. Any circuit into which current flows can be inductive or noninductive, so a synchronous motor can be inductive or noninductive, depending upon the strength of its field. If the field is weak or there is none at all, the current flowing will lag exceedingly behind the applied e. m. f., so that the energy component of this entering current will be very small.

OPEN CIRCUIT IN FIELD.

Thus, on a 100-horsepower synchronous motor, if the field is broken, not more than 15 or 20 horsepower can be put on without excessive heating, due to the fact that for each horsepower a large amount of current is necessary as compared to the amount per horsepower with proper field strength. Likewise, if the field is too strong, a similar excess—but in this case a "leading" current—is required per horsepower. It is a fact that a certain definite field current is required for the entering armature current to be in phase with the applied e. m. f. making each ampere an "energy" ampere instead of a lagging or leading ampere idle as far as energy is concerned.

Expressed in another way; if the magnetism which the field produces tends to decrease due to weakening

G. E. SYNCHRONOUS MOTOR WITHOUT ROTOR.

the field, a lagging current will flow into the armature producing magnetism equal to that which the field fails to produce, for the ampere turns of the armature current act in the same magnetic circuit as the ampere turns of the field circuit and lagging current is a magnetizing current in a motor. Expressing this in a curve it appears as in Fig. 30. At the point *b* the field current gives the

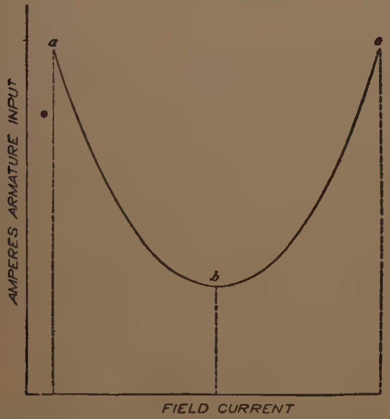


FIG. 30. EFFECT OF VARYING FIELD CURRENT ON THE ARMATURE CURRENT REQUIRED FOR A GIVEN OUTPUT.

minimum armature amperes input for the horsepower output in question. As the field current decreases, the armature current rises. As the field current increases above *b* the armature current again rises.

If, therefore, in the operation of a synchronous motor

the field current breaks for any reason, the armature current will largely increase causing either a shutdown, or excessive heat. It becomes important, therefore, in synchronous motors to have the field current permanently established.

DIFFICULTIES IN STARTING.

More than an induction motor a synchronous motor is weak in its starting as compared with its running torque. In general, however, a synchronous motor will start itself and perhaps one or two other machines connected to it, but without any load. This starting requires no field current as the flux which tends to start the motor is not the flux that keeps it operating when up to speed. In starting, therefore, the field current, under these conditions, is highly lagging, and, since a lagging current on any circuit tends to pull down the voltage on that circuit, the current on a synchronous motor when starting tends to lower the voltage applied to it. The starting torque, as in an induction motor, is in proportion to the square of the applied voltage. For instance, if the voltage is halved, the effort to start is only one-quarter. When, therefore, a synchronous motor will not start, it may be due to the fact that the voltage on the line is pulled down below the value necessary for starting.

In general, at least, half voltage is required to start a synchronous motor. Difficulty in starting may also be caused by an open circuit in one of the lines to the motor. Assuming the motor to be three-phase, if one of the lines is open-circuited the motor becomes single-phase,

and no single-phase synchronous motor, as such, is self-starting; the motor will, therefore, stand still, and soon get hot. The same holds true with a two-phase motor, if one of the phases is open circuited.

Difficulty in starting may be due to a rather slight increase in static friction, due to bearings being too tight, perhaps from cutting during the previous run introducing extra friction at the time of the next starting; extra tension on the belt in case the synchronous motor is belted to its load, or any cause which has added friction requiring additional starting torque. Difficulty in starting may be due to the fact that the field excitation is on the motor. After excitation passes above one-quarter its full value, the starting torque is influenced and, if full field is on, most synchronous motors will not start at all. If the voltage applied to the motor is proper, the circuits all closed except the field circuit and the friction is known to be as low as possible and still the motor will not start, the fault is with the manufacturer. Often the pole pieces receive extra windings or there are bridges provided between the pole pieces to assist in starting and it is possible that the manufacturer in shipping may have left these devices out. Under such circumstances the only thing to do is to refer back to the factory.

Usually compensators are used for starting synchronous motors and, if there is a reversed phase in the compensator, or, if the windings of the armature of the synchronous motor are connected incorrectly, there will be no large starting torque. This condition of incorrect connection can be found by noting unbalanced entering currents. This unbalancing should be taken with the

WAGNER SINGLE-PHASE SYNCHRONOUS MOTOR.

armature revolved slowly by any mechanical means. Standing still, even with correct connections, the three armature currents usually differ somewhat, due to the position of the poles as related to the armature, but when revolving slowly, these should average up. If this mechanical revolving cannot be performed, similar points on each phase of the armature must be found and when these points are set in a similar position to a given pole piece the currents in the three phases respectively should be the same. In other words, each phase when set in a certain specific position as related to a pole, should take a certain specific current, with right connections. With wrong connections under these similar positions, the currents would not be the same.

SHORT CIRCUIT IN ARMATURE COIL.

Unlike an induction motor, a short circuit in the armature of a synchronous motor burns it out completely, charring it right down to the bare copper. When this occurs, the physical symptoms are so clear that there is no difficulty in identifying the trouble. Such a coil may be cut out and operation continued under ordinary circumstances. It will be remembered that, in an induction motor, the current in the short circuited coil only rises to a certain figure, heating it many times more than normal but not necessarily burning it out immediately, or perhaps not at all.

BEARING TROUBLES.

These are similar to those that have been described for induction motors, the only difference being that, with a synchronous motor, the air gap between the revolving

element and the poles is quite large, so that the wearing of the bearing, throwing the armature out of center, is not the serious proposition that it is with an induction motor. In this respect the synchronous motor has an advantage over the induction motor. End play is caused by the same phenomenon and should be treated the same as in the case of an induction motor.

PULSATION.

Synchronous motors, under certain primary sources of energy, tend to "hunt." This phenomenon is a mechanical swinging of the armature accompanied by a similar swinging of the current input. The periodicity of this swinging depends upon the condition of the armature and the circuit. It may reach a certain magnitude and there stick, or the swinging may get larger and larger until finally the motor breaks down altogether. This trouble is usually on long lines where there is considerable resistance between the primary source of energy and the synchronous motor although sometimes it may occur under the most favorable conditions in this respect. An irregular rotation of a prime mover such as a single-cylinder steam engine is often responsible for the trouble. The usual remedy is to apply to the poles pieces of copper or brass in which currents are induced by the wavering of the armature, which currents tend to stop the motion. These pieces of metal are usually designated as bridges. Different companies apply different forms of bridges to accomplish the purpose. When this hunting or pulsating occurs, therefore, it is best to consult with the manufacturer as the curing requires such special experience that

it would hardly do to experiment. In general, the weaker the field on a synchronous motor, the less the pulsation. In cases where satisfaction results with minimum input, trouble might result with a stronger field when the entering current would be leading. In many installations, more than normal current is used on synchronous motors. Under this condition, the entering current is leading the applied e. m. f. and the result is that the voltage on the line is assisted by this leading current, the facts being that lagging current passing through inductance tends to lower voltage, while leading current passing through inductance tends to raise voltage. Therefore sometimes pulsation may be brought down to a point where no trouble results by simply running with a somewhat weaker field current.

Grounds and excessive noise are covered in the discussion on induction motors.

IMPROPER ARMATURE CONNECTION.

This usually manifests itself in a synchronous motor by unbalanced entering currents and by the fact that the starting torque is very much less than it should be, or perhaps negligible. The circuits should be traced out and the connections remade until the three entering currents in the case of three-phase, or the two entering currents in case of two-phase, agree approximately. It should be noted, as previously stated, that these currents do not agree even with correct connection when the armature is standing still. The reading should be taken with the armature revolving slowly, mechanically, which,

with the proper connection, should average up the entering currents.

POLARITY.

Since the winding of a synchronous motor armature is in series all the way around the circumference and under all of the poles, except in exceedingly rare cases, the trouble from a reversed pole is much less serious than in the case of an induction motor or direct-current machine, everything operates fairly satisfactory, the only trouble being that the fields require more current than they should to make up for the pole that is opposing the other fields. If, therefore, excessive field current is required for the minimum input to the motor, it would be well to try the polarity of all the spools, using a compass for the purpose.

PART III.—THE TESTING OF DIRECT-CURRENT MACHINERY.

CHAPTER X.—TESTING GENERATORS.

DIRECT-CURRENT GENERATORS.

IT HAS become customary among manufacturers of high grade electrical apparatus, in filling orders, not to allow a machine to pass from their shops without first testing it to determine whether or not it operates according to the standard guarantees written for it.

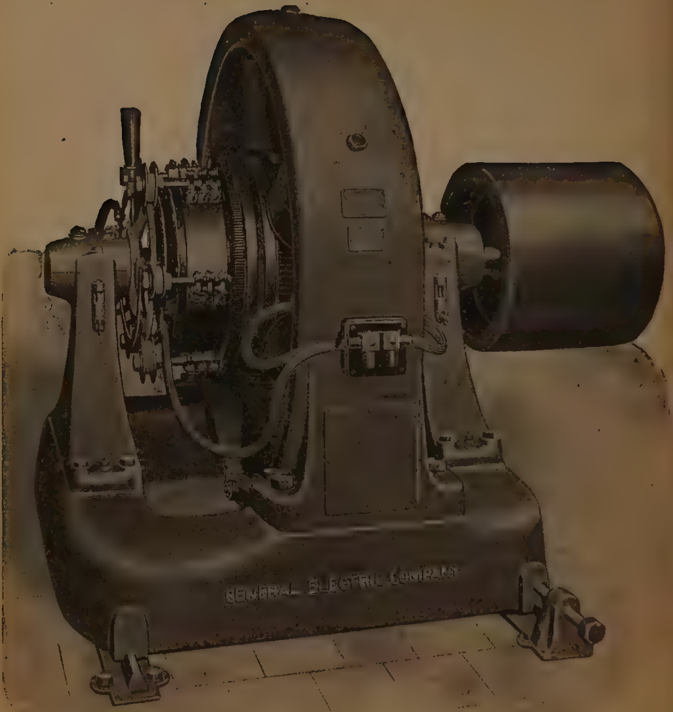
TEMPERATURE TESTS.

The testing of a direct-current generator consists in obtaining information on the following matters:

1. The temperatures of all parts of the generator after it has been carrying full load sufficiently long for such parts to have attained a constant temperature.

The American Institute of Electrical Engineers gives as the standard temperatures for commutating machines, 50 degrees C. rise by resistance in field or armature; 55 degrees C. rise by thermometer in commutator, collectors or brushes, and 40 degrees C. rise by thermometer in bearings.

These temperatures may be departed from without immediate damage to the machine, but as a generator properly designed and built should last indefinitely, its temperature of operation should be such as not to injure the insulation in the slightest degree. Also the iron in the core of the armature, the loss in which has the commanding influence on the efficiency, must operate at a tem-



GENERAL ELECTRIC DIRECT-CURRENT GENERATOR FOR RAILWAY WORK.

perature that will not produce any ageing within itself. In general, a machine of abnormal temperature means one of low efficiency. Another trouble resulting from too high a temperature is the variation in resistance of the field spools and armature, for while they are heating up to their final values, it is necessary to continually adjust the rheostat in series with the shunt field if it be desired to keep the voltage constant.

The connections for the shunt field of a generator are shown in Fig. 31. The rheostat *A* and the field *B* are

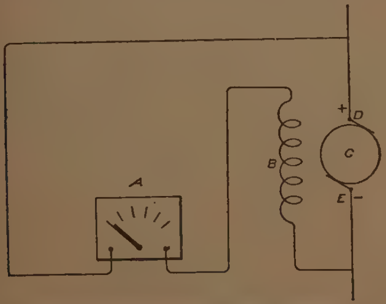


FIG. 31. CONNECTIONS FOR THE SHUNT FIELD OF GENERATOR.

joined in series and connected to the brushes *D* and *E*, from the latter of which is obtained the electromotive force producing the field current. If it be desired to maintain a constant electromotive force between *D* and *E*, it becomes necessary to keep the current in *B* approximately uniform in value. If the resistance of *B* as well as that of the armature *C* increases abnormally, it must

be neutralized by reducing the resistance in the rheostat A by a certain amount that will keep the field current at the desired value.

In a series machine, if the resistance of the series field varies considerably from cold to hot, there will be a variation in the division of current between this machine and another with which it may be running in multiple; this, of course, necessitates hand adjustment of the field rheostat for a proper division of the current.

METHODS OF LOADING.

Several methods are employed in testing rooms for getting a machine to its operating temperature. One way consists in using a resistance of such a value that full load will result when connecting it in the dynamo circuit. A box of water salted more or less constitutes a good resistance. The box may be of iron, tapering inward toward the bottom, and into this should hang an iron plate, Fig. 32. One terminal of the circuit is connected to the box, and the other terminal to the plate. The resistance of the circuit decreases as the plate is lowered into the water, both on account of the decreasing distance between the sides of the box and plate, and also on account of the increased area of the plate exposed to the water. A box containing about 20 cubic feet of water will readily carry 150 kilowatts. A more economical way of accomplishing the same result is by means of the Hopkinson method, which consists in feeding back one machine upon another. Under these conditions, however, it is necessary to employ two machines. A third way is to short circuit the machine upon itself. These

two latter methods will be described in the section on temperatures under overloads.

OVERLOAD TEMPERATURE TESTS.

2. The temperatures of all parts of the generator after it has been carrying a specific overload for a reasonable time.

The American Institute of Electrical Engineers advises as to overloads for direct-current generators, 25

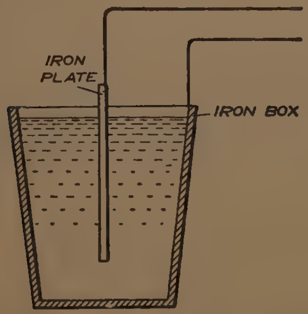


FIG. 32. WATER RHEOSTAT FOR LOADING DYNAMO.

per cent overload for two hours with an increase of temperature not exceeding 15 degrees C. above that specified for full load; the overload to be applied after the apparatus has acquired the temperatures corresponding to full load continuous operation. Since there are times in the operation of a generator that it may be required to perform unusual work for short periods, generators should possess a reserve capacity which will

REVOLVING FIELD COIL STRUCTURE, GENERAL ELECTRIC CO.

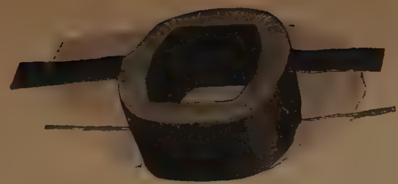


Fig. 608A

DETAILS OF FIELDS AND COIL WINDINGS.

Fort Wayne Electric Co. Crocker-Wheeler Co. Northern Electric Co.

enable them to pass this test. Under such circumstances it is permissible to encroach somewhat upon normal conditions, and yet not inflict real injury upon the machine.

The Hopkinson method of "feeding back" one machine upon another requires connections similar to those shown in Fig. 33. Here some source of electrical energy

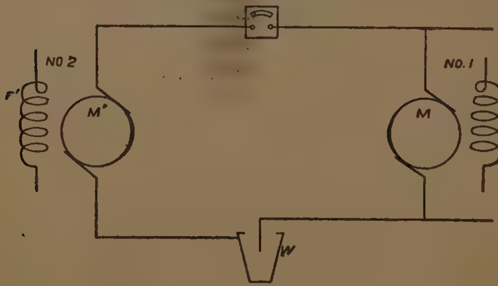


FIG. 33. CONNECTIONS FOR HOPKINSON METHOD OF LOADING A DYNAMO.

supplies the losses. *F* is the field of generator No. 1, and *F'* the field of generator No. 2; *M* represents the armature of generator No. 1, and *M'* the armature of generator No. 2. The armatures *M* and *M'* are mechanically connected together either by a belt or direct connection. The method of procedure is as follows: Start up the generators No. 1 and No. 2 by running them both as motors. Weaken the field of No. 1, and it will run as a motor, being fed by No. 2, which will then be running as a generator. The losses will be supplied by the source of energy. The action causing the flow of current has

been so often described that it will not be necessary to repeat it here. The two generators M and M' need not be of the same voltage; if M' gives a higher electromotive force than M, a water box may be inserted at W to use up the excessive voltage. In case it be desired to keep the two fields F and F' at the same strength, a booster giving a voltage equal to that used up in the resistance of both armatures, brushes, and wire, can be inserted in circuit. The booster will circulate the current, and the circuit from outside will supply the losses as before.

Another method of loading a generator without running an actual energy load, consists in short circuiting the generator upon itself. At first thought one would imagine that under such circumstances the amount of

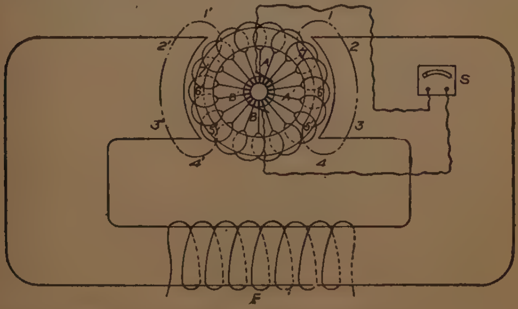


FIG. 34. SHORT-CIRCUIT METHOD OF LOADING A DYNAMO.

flux through the core would be small, so that a true heating effect would not be obtained. But let us consider Fig. 34. This diagram represents a generator with

brushes at A and B, and the field winding at F. When current flows through the ammeter S and the armature, the armature current itself sets up a flux in the path 1, 2, 3, 4, 5, 6, 7, and in multiple with this another flux is also set up in the path 1′, 2′, 3′, 4′, 5′, 6′, 7′, as shown by the broken line. This flux resulting from full load current is not far from normal, and the voltage between the points A' and B' is also not far from normal. Thus we have a condition of 0 voltage between brushes, and approximately full voltage 90 degrees away from the line of brushes. Such a condition is more than ordinarily severe as to sparking, but with proper experience one can judge of the quality of commutation this way as well as in the normal way. This method is, therefore, an extremely valuable one for loading very large generators or motors, requiring but little energy for a heat run and yet providing us with full load results. The temperature of the fields F must be obtained separately by running the machine with normal field current, but with no load in the armature.

COMMUTATION TEST.

3. The commutation at full load, and at various overloads; also at full voltage, and at various other voltages.

The loads to be used for judging commutation may be obtained by any one of the methods explained in the preceding section. A good machine should run sparklessly at full load, may show some slight sparking at 50 per cent overload, and should stand double load momentarily

without injury, though it must be expected under such conditions that considerable sparking will ensue.

The various degrees of sparking that may be expected at the commutator under different loads is illustrated in

FIGS. 35-40. DEGREES OF SPARKING UNDER VARIOUS LOADS.

Figs. 35-40 inclusive. In Fig. 35 is shown the way a machine should run at full load, though the conditions presented in Fig. 36 would be called fair. At 50 per cent

overload, Fig. 37 illustrates the amount of sparking that might properly be expected, though that shown in Fig. 37 would be termed fair. Fig. 39 or a somewhat worse state of affairs is what might be expected at double load.

A well designed machine will carry full load current down to 0 voltage without any particular trouble as to sparking. The usual appearance of the commutator under this test is illustrated in Fig. 40.

CORE, FRICTION AND RESISTANCE LOSSES.

4. The core loss, friction loss, and the resistance losses of field, armature, and brush contact.

An excellent method to employ for measuring the summation of these losses consists in applying to the brushes of the generator a voltage equal to the normal voltage of the generator plus the voltage drop in the armature winding and brush contact. On a motor, the applied voltage should be the normal voltage minus the voltage drop in the armature winding and brush contact. The field of the machine should be varied till normal speed is obtained. Since "running light" in this manner requires but little current, the applied electromotive force equals the back electromotive force, and this equals the generated electromotive force existing when the machine is operating as a generator at full load. The normal full load flux is thus obtained at normal speed, and hence the input gives the summation of all the losses. If the resistance losses of field, armature, and brush contact existing during the "running light" reading be subtracted from this total loss, the value of the

WESTINGHOUSE MOTOR-DYNAMO DIRECT-CURRENT BOOSTER SET.

core and friction losses will be obtained. This is the "stray power" method of Hopkinson, and is a perfectly satisfactory method for obtaining the efficiency of a dynamo. If it be desired to separate the core loss from the friction losses, it is necessary to belt to the generator of which the core loss is required, a motor of such a size that it will be about half loaded when the maximum energy of the generator loss is being registered. This is necessary in order to avoid as far as possible any armature reaction and variation of flux, and hence core loss, in the driving motor itself, the core and friction losses of which should remain as nearly constant as possible. It is also preferable to use copper brushes on the driving motor in order to avoid the variation in brush contact resistance which exists when carbon brushes are employed. The field of the driving motor should be maintained at constant strength throughout the test. A glued belt should preferably be employed to avoid the pulsation which may result from the use of a laced belt. The belt tension should be as light as possible to run without slipping, and the bearings should not heat or change in temperature during the test. As field current is supplied to the generator whose core loss is being measured, the load on the driving motor will increase. In order to maintain constant speed, the voltage applied to the driving motor must also be increased. The increase should be practically equal to the indicated voltage drop across the motor armature and brushes. If it be different, the belt is slipping, or a motor has been chosen which gives trouble owing to armature reaction,

or a varying flux. If the motor be properly chosen, the brushes will require no shifting.

The input of the driving motor, less its resistance loss when running the generator under normal field, minus the input of the motor less its resistance loss when running the generator without field, gives a measure of the generator core loss at the field used.

The input of the driving motor less its resistance loss, when running with belt off and at proper speed, subtracted from the input less its resistance loss when belted to the generator without field, gives a value of the friction of the generator In obtaining these inputs of the driving motor, sufficient time must be allowed for all acceleration or retardation to cease, otherwise an incorrect value will be obtained.

During the time in which the core loss readings are being taken, the brushes of the generator should be exactly at the neutral point; there will then be no flux, and no energy will be consumed by local currents beneath them.

The curve of core loss takes the form shown in Fig. 41. It should be noted that since hysteresis varies as the 1.6th power, the core loss at B should be over three times that at A if the volts at B are twice those at A. This furnishes a simple and rapid way to check a core loss curve which has been obtained.

MEASURING RESISTANCE OF ARMATURE AND FIELD.

The resistance of the field winding can best be measured by an ordinary Wheatstone bridge. The resistance of the armature, however, should be obtained by the

"drop method," that is, by passing through it a current preferably of a value near that of the normal armature current, and recording the necessary voltage at the commutator bars to produce this current. The voltage at the

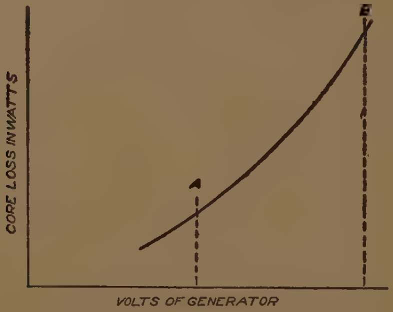


FIG. 41. CORE LOSS VARIATION WITH E. M. F.

bars being usually very small, is somewhat difficult to secure, but with special care, can be obtained with sufficient accuracy. These resistances should be taken both hot and cold so that the rise in temperature by resistance can be calculated by the usual formula:

$$R_T = R_0 (1 + St)$$

When this formula is used for copper, $S = 0.0042$.

The rise in temperature of a winding thus calculated is usually 50 per cent more than when obtained on a thermometer, since the latter only registers the outside temperature, while the former takes into account the temperature of the entire winding. On an armature this

difference is about 25 per cent, but on a field spool it may be as high as 80 per cent.

BRUSH CONTACT RESISTANCE.

The brush contact resistance for carbon brushes will be found to be 0.028 ohm per square inch at ordinary speeds. This, however, is an average value. It varies with the density of current flowing, ranging from about 0.040 per square inch at a density of 15 amperes per square inch to 0.022 per square inch at a density of 60 amperes per square inch. At a given density, say 30 amperes per square inch, the brush contact resistance varies from 0.028 ohm at 1¾ pounds pressure per square inch to 0.035 ohm at ¾-pound pressure per square inch. With copper brushes, the value of contact resistance is about 0.1 of this, and the density of operation can go to 150 amperes per square inch. The brush contact resistance should be considered as a part of the armature resistance, and should enter into all the efficiency and armature drop calculations.

In calculating the loss resulting from friction of the brushes, a coefficient of friction of 0.3 may be used, and the usual operating of mechanical pressure may be taken between 1½ and 1¾ pounds per square inch.

EFFICIENCY AT VARIOUS LOADS.

5. A method has previously been outlined of obtaining the core loss, the friction loss, the resistance of field and armature, and the brush contact resistance. The efficiency of a generator therefore equals the output in watts, divided by the summation of the output in watts, the core loss, the field resistance loss, the armature resistance loss,

the brush contact resistance loss, and the total friction loss.

COMMUTATOR "SETTLING."

6. A commutator consists of many segments of copper separated from each other by insulation (usually mica about 0.030-inch thick) as well as from the shell and clamps holding them. For satisfactory operation, it is necessary that the mica separating the segments from each other does not extend above the wearing surface, and that no individual bar alters its position with respect to the other bars by the slightest amount. To accomplish this, the clamps must exert a force in each bar. If roughness appears when the machine is in operation, the clamps should be tightened until each bar is subjected to the proper force to hold it in position. When this is done, the commutator surface should be smoothed and polished, after which it should run indefinitely without further trouble. The "settling" of a commutator may take considerable time, but no reputable manufacturer should ship a generator without the determination of a stable state of its commutator.

INSULATION RESISTANCE AND DIELECTRIC STRENGTH.

7. The American Institute of Electrical Engineers recommends for insulation resistance a value on the complete apparatus, such that the rated voltage will not send more than $\frac{1}{1,000,000}$ of the full load current through it. When the value found in this way exceeds 1 megohm, the insulation resistance is sufficient. The insulation

resistance of a machine varies considerably with the weather and degree of dampness of the surroundings. It can quickly be lowered by dampness and raised by baking in a dry chamber.

A convenient way to measure insulation resistance is to insert a voltmeter of known resistance R in series between the winding whose resistance is to be measured, and the ground or a part of the machine from which the winding is supposed to be insulated, Fig. 42. If X

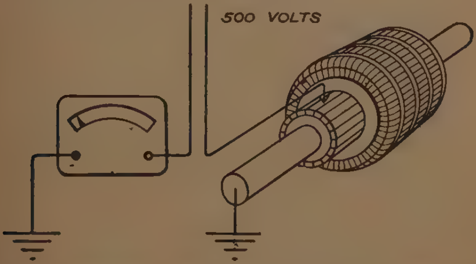


FIG. 42. CONNECTION FOR TEST OF INSULATION RESISTANCE.

equals the insulation resistance desired, R equals the voltmeter resistance, V equals the voltage of circuit (say 500) used to measure the insulation, and D equals the deflection on scale of voltmeter, then since according to Ohm's law the deflection is proportioned to the resistance,

$$\frac{R}{X} = \frac{D}{500 - D} \text{ or } X = R\left(\frac{500}{D} - 1\right)$$

Of more importance than the insulation resistance is the dielectric strength. For this, the American Institute

of Electrical Engineers recommends for apparatus rated between 400 and 800 volts, 2,000 volts "high potential" applied one minute, the application to be between circuits normally running insulated, and between these circuits and ground. This test should be made on the generator while it is at its normal operating temperature, and with a sine curve of electromotive force and normal operating frequency. Most manufacturers use a higher voltage than that recommended by the Institute. On railway apparatus, for example, it is common to test all parts with 5,000 volts.

MECHANICAL MATTERS.

8. (a) Proper mechanical balance of revolving element.

The armature should run free from any vibration. If vibration occurs, the armature must be put in a lathe, if one large enough is available, and the armature shaft straightened. The armature should then be placed on balance ways and its balance checked, and then replaced in the bearings to see if it rotates without noise. The best results cannot be obtained if the armature be unbalanced.

(b) True running parts.

This is merely a matter of appearance, but a piece not running true indicates carelessness on the part of the manufacturer:

(c) Freedom from undue noise.

Noise may result from chattering of the brushes, or from a magnetic hum. If the former, two methods exist to stop the trouble. First may be mentioned lubrication;

GENERAL ELECTRIC DIRECT-CURRENT GENERATOR DRIVEN BY STEAM TURBINE.

this ordinarily means the attention of an attendant, or the use of a lubricated brush of proper hardness and freedom from gumming. The second method consists in placing the brushes so that they form the proper angle with the commutator. This angle is an important feature in brush holder design, and if improperly chosen may cause considerable noise. Where a magnetic hum appears to be the trouble, there is probably a too sudden entrance of the armature teeth under the poles. In this case a champfering of the polar horns may remedy the trouble. At all events the point should be checked before shipment.

(d) Proper turning of the oil rings.

The oil rings for lubricating the bearings should certainly start to turn at one-quarter normal speed, and they should carry up and deliver to the oil rings a proper amount of oil.

(e) Freedom of bearings from leakage of oil.

Many excellent machines become unsightly and gather dirt which injures the insulation, on account of the fact that their bearings throw or leak oil. Bearings should be designed to give dry results, and all generators should be investigated with this fact in mind.

(f) Proper end play.

By proper end play is meant a free floating movement of the armature from side to side with a tendency for it to return to a central point half way between the limits of the thrust collars on the shaft. The magnetic pull will sometimes force the armature against the thrust collar

so hard as to cause undue heating; this matter should therefore be given attention.

(g) Uniformity of air gap.

A measurement should be made to see that the armature is mechanically centered in the frame. This may be done with a metal wedge which, when pushed into the gap, shows the amount of clearance by the distance it enters therein before binding.

(h) The general appearance of the machine.

The general mechanical condition of all parts should be investigated, and any defects corrected. Inspections are easily made by a properly trained tester, but they are both important and necessary for high class work.

ABILITY OF THE GENERATOR TO BUILD UP.

9. In certain cases considerable trouble may result if a generator does not build up when connected according to its print. This is especially true when many generators are connected in multiple with series fields. In order for the generator to build up, a certain terminal of the shunt field winding must be connected to a certain brush. This requirement exists regardless of the initial magnetism of the generator.

In Fig. 43, C and D represent the terminals of the shunt field winding Y, and A and B the leads from the armature X.

In order for this generator to build up, C must be connected to A and D to B irrespective of the polarity of the residual magnetism. For the opposite rotation of the armature, C must be connected to B and D to A. It is thus seen to be important that the operation of the gen-

erator be checked with the print, and corrected if found to differ therefrom. The trouble may result from an improper assembling of the field spools or from a wrong

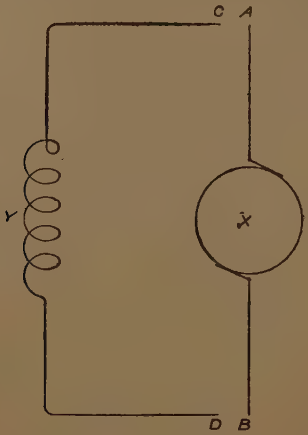


FIG. 43. SHUNT WINDING AND ARMATURE.

progression of the armature winding, or from an incorrect print.

SHAPE OF THE COMPOUNDING CURVE.

10. The compounding curve shows the relation between the load or current and the volts at the terminals of the machine. The variation from the desired compounding at any point is generally known as the "hump" of the curve. The United States government allows a maximum variation of 2 per cent when starting at the de-

sired voltage and returning to the same voltage. This must also include any variation that may occur in engine speed. On a commercial generator one should expect a maximum variation of not over 3 per cent. Such a compounding curve would therefore resemble the one shown in Fig. 44 for a 125-volt generator.

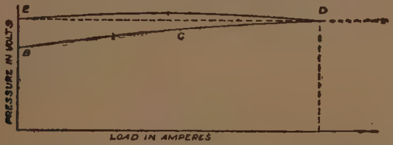


FIG. 44. COMPOUND DYNAMO CHARACTERISTIC.

This curve starts at *B*, runs to *D* at full load as indicated by the arrow, and then returns to *E* at no load. The departure of this curve from the dotted line *E* which represents a constant pressure of 125 volts, should not be over 3 or 4 per cent.

A curve derived from the one in Fig. 44 should be recorded for future design as well as for data on individual operation. Such a curve is shown in Fig. 45.

The point *A* on this curve gives the ampere-turns for no load, and the point *B* those for full load.

The brushes on a carbon brush machine should be stationary; they should be set forward at no load, an angular distance around the commutator.

This distance should be such as not to give appreciable sparking at no load, and no sparking at full load. This is known as the "brush shift" of the machine. It

should be as small as possible, yet consistent with the best operation for the armature-turns embraced by the double angle. In fact, the compounding ampere-turns are composed of these back ampere-turns on the arma-

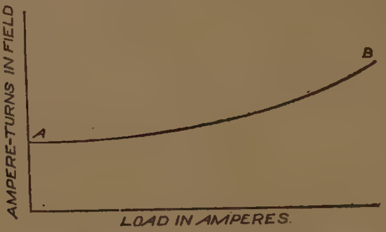


FIG. 45. AMPERE-TURN CURVE FOR COMPOUND DYNAMO.

ture and of the extra ampere-turns due to leakage, together with the actual increase of flux necessary for all the resistance drops, and the variation of flux density in the pole faces due to armature distortion.

THE SHUNT CHARACTERISTIC.

11. In a shunt machine, the shape of the curve which shows the drop in voltage as the load is increased under a constant magnetomotive force.

Such a curve resembles that shown in Fig. 46. The line *AB* represents the voltage which, in this case, equals 125. At one-quarter load the voltage has fallen to *G*. Increasing it again to 125 volts or *C*, and adding another quarter load, it drops to *H*. Raising it to *D* and adding another quarter load brings it to *I*, and so on. A properly designed machine will drop as shown, but

will not unbuild with quarter load variations. The variation at *G, H, I,* and *K* grows larger as full load is approached; *FK,* for example, being greater than *CG.*

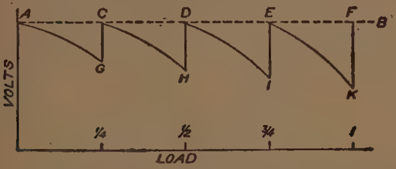


FIG. 46. DROP CURVE FOR SHUNT MACHINE.

THE SATURATION CURVE.

12. The saturation curve takes the form shown in Fig. 47. As the ampere-turns increase, the volts in-

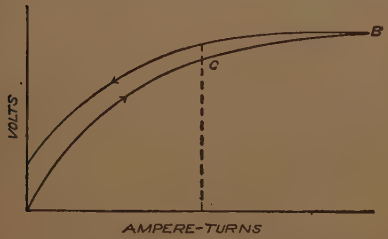


FIG. 47. SATURATION CURVE FOR DYNAMO.

crease. At the point *C*, however, the increase of volts diminishes appreciably. A generator should be operated just above the point *C* to obtain stability and freedom from "unbuilding." No unbuilding can result above *C*, since the volts are then no longer proportional to the

ampere-turns, and perfect balance can be secured. When the volts are proportional to the ampere-turns, the voltage will wander up and down, usually unbuilding the machine, or rushing up the voltage to a "flashing over" point. For this curve, the brushes should be placed at the geometrical neutral point, and it should be seen that the presence of the brushes upon the commutator do not create a magnetomotive force due to local currents beneath them. On concentrated designs, this brush effect may be considerable.

THE DROP OF POTENTIAL THROUGH THE SERIES WINDING.

13. This drop of potential should be the same at normal current on all sizes of generators that may ever be run in multiple, the resistance being that of series coils, including series shunt, if one be used; otherwise, an equal distribution of load will not result under these conditions. This value should therefore be read, recorded, and checked.

POTENTIAL CURVE OF THE COMMUTATOR.

14. On multiple-wound armatures, the voltage between any one brush and the next brush in order to it in both directions, should be obtained. A variation of not over 4 per cent should be allowed; otherwise, cross currents will exist which will lower the efficiency and injure the ability of commutation. This test cannot be applied to series-wound armatures, or to those that are cross-connected; in such cases, reliance must be placed upon the mechanical centering of the armature.

VOLTAGE AT NO LOAD WITH FIELD RHEOSTAT ENTIRELY CUT OUT.

15. This reading should be taken with the field winding at normal operating temperature, and at a brush shift that will permit it without flashing; it shows the maximum power of the field to produce voltage. In hot climates, the resistance of the shunt field is higher, and the margin in the field rheostat is cut down materially over what it would be on a cold day in a cold climate.

NORMAL VOLTAGE DROP IN FIELD RHEOSTAT AT NO LOAD.

16. This is as important a reading as the one in Section 15. The brushes should be in their normal operating position, and the field should be at its normal operating temperature. The drop in the field rheostat should be sufficient to allow for variation of climate and of load. The minimum drop should be about 12½ per cent, and the maximum drop about 40 per cent.

VOLTAGE DROPS ACROSS FIELD SPOOLS.

17. The resistance of the shunt and series windings on the different spools of a generator should be the same. A variation of 10 per cent, however, is allowable under usual conditions, without affecting the potential curve or the individual spool temperatures.

CHAPTER XI.—TESTING DIRECT-CURRENT MOTORS.

DIRECT-CURRENT motors, in general, require tests similar to those for a direct-current generator. Thus, the various temperatures of a motor under full load should be obtained as described in Section 1, under the head of Direct-Current Generators, Chapter X. The Hopkinson method may be used in loading the motor, or a water box may be employed in connection with a generator belted to the motor and acting as a load. In a motor, the variation of resistance in the field winding produces variation of speed. The temperature of the field winding must therefore be maintained sufficiently low, that the variation of speed resulting from the resistance variation be less than 6 per cent. The American Institute of Electrical Engineers allows 50 degrees C. rise in temperature of the field winding by increase of resistance.

The various temperatures of a motor under overload should be obtained as described in Section 2, Chapter X.

The commutation of a motor at full load, and at various overloads; also at full voltage and at various other voltages, should be obtained as described in Section 3, Chapter X.

The core loss, friction losses, and the resistance losses of field, armature, and brush contact should be obtained as described in Section 4, Chapter X.

DIRECT-CURRENT ENCLOSED TYPE MOTOR. FT. WAYNE ELECTRIC WORKS.

The efficiency of a motor equals the input in watts, minus the sum of the core loss, field resistance loss, armature resistance loss, brush contact resistance loss, and total friction loss, divided by the input in watts.

Information as to the settling of a commutator in a motor should be obtained as described in Section 6, Chapter X.

Information as to the insulation resistance and dielectric strength of a motor should be obtained as described in Section 7, Chapter X.

Information as to the mechanical matters to be investigated in motors should be obtained as described in Section 8, Chapter X.

A motor does not have to build up as mentioned in Section 9, Chapter X, but a certain connection of the field spools gives one direction of rotation, and a reversed connection gives the opposite direction of rotation. The direction of rotation of a motor should therefore be checked with the print, relatively to the connection of the field spools.

REGULATION FOR CONSTANT SPEED.

Corresponding to the compounding curve described in Section 10, Chapter X, is the regulation curve in the case of motors. The regulation curve shows the change in speed of a motor from no load to full load, and also from a cold condition to a hot one. The curve is taken by gradually loading the motor when hot and when cold, and noting the corresponding speeds; these results, when plotted, give the two curves shown in Fig. 48.

The curve *DA* represents the variation of speed with

load when all parts of the motor are at running temperatures. The curve *CB* represents the variation of speed with load when all parts of the motor are cold. The point *A* at full load should not be over 60 per cent above

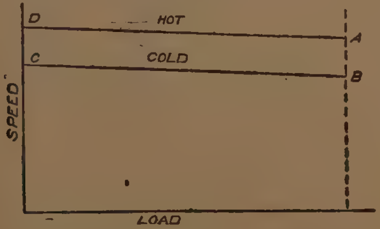


FIG. 48. REGULATION CURVE FOR DIRECT-CURRENT, SHUNT-WOUND MOTOR.

the point *B* at full load; the point *A* should not be more than 5 per cent below the point *D* at no load; and the point *B* should not be more than 5 per cent below the point *C* at no load. In some motors, the point *A* may actually be higher than *D* owing to very large armature reactions. Such motors are sometimes dangerous for the reason that the effect of the armature may entirely overcome that of the field, and cause an unsafe speed if much overload is placed upon the motor.

VOLTAGE TESTS.

The potential curve of the commutator in a motor should be obtained as described in Section 14, under Chapter X.

The voltage drops across the field spools of a motor should be obtained as described in Section 17, Chapter X.

STARTING BOX FOR DIRECT-CURRENT MOTOR.
GENERAL ELECTRIC CO.

STARTING BOXES FOR DIRECT-CURRENT MOTORS.
WESTINGHOUSE ELECTRIC CO.

Although the details in handling the instruments for these measurements have not been mentioned, it is evident from what has already been stated, that proper calibrating facilities must be provided, and that care in the placing and handling of the instruments is necessary in order to secure the best results.

In conclusion, it may be stated that the tests described in this chapter can be applied to any generator or motor within a reasonable length of time, and that an absolute guarantee of operation can be obtained for a moderate expenditure of money. As a high-class insurance of future satisfaction to a customer, such testing is of inestimable value.

PART IV.—TESTING ALTERNATING CURRENT MACHINERY.

CHAPTER XII.—ALTERNATING-CURRENT GENERATORS.

AFTER the various parts of a generator have been produced in the different departments of a manufacturing company, it becomes necessary to assemble and test the complete machine, not only to prove that it will go together and operate without difficulties, but that the various electrical characteristics are in accordance with guarantees, if any have been given, or in accordance with the accepted standard held by that particular manufacturing company.

The mechanical and electrical characteristics of importance to a customer, and of course to a manufacturer, in an alternating-current generator consist of the following:

1. Efficiency at all loads, and incidentally in connection with this, the various losses that make up the efficiency.

2. The regulation, both at 100 per cent power factor and at other power factors, depending upon the kind of service for which the generator is to be used.

3. The temperatures of the various parts when operating under the conditions which may be met with when permanently installed.

4. The voltage and current necessary for the field when the ultimate temperature resulting from the quality of load requiring the greatest field excitation is reached.

5. A demonstration of the ability to withstand short-circuit upon the armature, the short-circuit to be applied close to the machine, and with the generator operating at normal voltage.

6. Wave shape of the machine when running at various loads and normal potential.

7. Insulation resistances of all windings.

8. Ability to withstand not only normal potentials in the windings, but higher potentials applied with the machine hot, to demonstrate the factor of safety of this feature.

9. Noise of operation.

10. Quality of insulation used.

11. Method used to apply insulation and to wind coils.

12. Ability to withstand a certain percentage excess in speed.

13. Satisfactory operation of bearings.

14. Rotation of phase.

15. Satisfactory mechanical details of the various parts.

We will consider these various items in the order just given.

EFFICIENCY AT ALL LOADS—VARIOUS GENERATOR LOSSES.

The efficiency of a generator is the ratio of the output in electrical energy to the input in mechanical energy. Thus, the output equals the input minus the losses. These losses consist of the following:

Friction and windage.

Core loss.

REVOLVING FIELD ALTERNATOR; CROCKER-WHEELER CO.

I^2R loss in armature winding, where I = current and R = resistance.

I^2R' loss in field winding.

I^2R'' loss of brush contact.

Load losses.

CONNECTIONS FOR TEST.

To obtain the friction and windage and core loss, the best method is to belt to the alternator a direct-current motor. Connect an ammeter in the armature circuit of

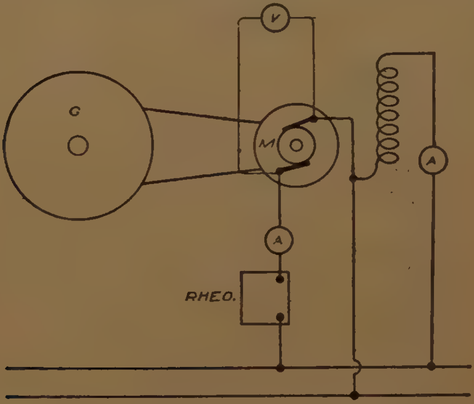


FIG. 49. ARRANGEMENT AND CONNECTIONS FOR TESTING OUT EFFICIENCY OF GENERATORS.

the motor and also one in the field circuit. Connect a voltmeter across its brushes. Then the input to the motor at any instant when driving the alternator, which equals volts across armature $\times$ amperes in armature,

gives a measure of the energy represented by the friction and windage and core loss of the alternator, together with the friction windage, I^2R loss, and core loss of the driving motor, plus the loss in the belt used in connecting the direct-current motor to the alternator.

The brushes on the commutator consume a certain amount of energy due to the I^2R loss of contact resistance. Since carbon brushes have a variable contact resistance, depending upon the current density, which is approximately equal to 0.025 ohm at 40 amperes per square inch, and 0.045 ohm at 10 amperes per square inch, it is best to have the driving motor equipped with copper brushes. The contact resistance of copper brushes being only one-tenth that of carbon, is so small that it can be neglected.

The driving motor should be of such a size that when driving its alternator at its normal speed and with the maximum field current at which core loss is desired, that it will be loaded only to about half load. This is so that no particular shifting of the brushes on the motor will then be necessary, for it is to keep the core loss of the driving motor constant throughout, so that when subtracting the motor input (which includes its own core loss) with field off the alternator, from its input with field on the alternator, the core loss of the driving motor being the same in each case will disappear in the calculation.

MAKING THE TEST.

To this end, the field on the driving motor is kept perfectly constant throughout the core loss test by the ammeter in its circuit, and since the motor is so chosen

in size that it is but half loaded, the armature reaction has no influence upon the actual field flux of the motor.

If the motor armature reaction were large and if it were necessary to shift the motor brushes during the test, then although the motor field amperes were kept constant, an actual variation of motor flux, and hence of motor core loss, would result.

The motor being chosen and equipped as described a voltage V is applied to its armature so that the alternator at any given field excitation will run at normal speed. At this alternator field excitation, let the amperes in the driving motor $= I$. Let the armature resistance of the motor armature $= R$, and the core loss and friction of the motor $= K'$. Then $IV =$ the total watts input, and this includes the friction and windage of the alternator, which we will call F, its core loss which we will call K, and the loss in the belt, which we will call B. It also includes the core loss and friction of the driving motor, which we have called K'. Thus:

$$IV = F + K + B + K^1 + I^2 R \quad (1)$$

The field current is next removed, and if there be observable any residual magnetism in the alternator, the presence of which may be determined by a deflection in the voltmeter after the field current has been removed, it should be taken out by a slight touch of current through the field in the opposite direction. The input measurement of the driving motor is then repeated, its field being kept perfectly constant as in the previous reading. The new input then is:

$$I^1 V^1 = F + B^1 + K^1 + (I^1)^2 R \quad (2)$$

But B', the belt loss under the lighter load conditions, can properly be assumed the same as B under the load obtained with field on the alternator. If I^2R be calculated and subtracted from equation (1), and $(I')^2R$ be calculated and subtracted from equation (2), and if B' is assumed equal to B, we get from equation (1) the following:

$$IV = F + K + B + K' \tag{3}$$

Also, from equation (2):

$$I'V' = F + B + K' \tag{4}$$

Subtracting equation (4) from equation (3), we get

$$IV - I'V' = K$$

or the core loss of the alternator.

If, now, we read the input to the driving motor with the belt removed, we get

$$I''V'' = K' + (I'')^2R$$

and by calculating and subtracting $(I'')^2R$ from this we have:

$$I''V'' = K' \tag{5}$$

Subtracting equation (5) from equation (4), we get

$$I'V' - I''V'' = F + B \tag{6}$$

Equation (6) gives the friction of the alternator plus the belt friction and the extra bearing loss due to belt tension. Since the last named is negligible compared with the friction of the alternator proper, equation (6) gives a measure of the friction of the alternator. We thus have determined both the friction and the core loss. This process can be repeated for the full range of field

values of the alternator and a core loss can be obtained and plotted. It appears as shown in Fig. 50.

In obtaining a core loss as described, care must be taken before actually reading the input to be sure all acceleration and retardation have ceased, since these would alter the true input as recorded by the volts and am-

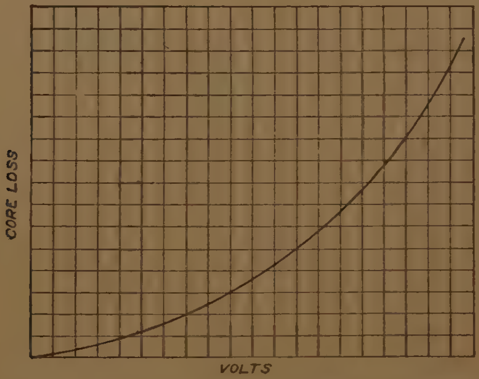


FIG. 50. CORE LOSS OF AN ALTERNATING-CURRENT GENERATOR.

peres to the motor. A constant source of energy, therefore, is needed. The volts V on the motor with field on the alternator should differ from the volts V' and V'' only by the difference in the I^2R drop in the driving motor armature; otherwise a flux variation is going on in the motor, and the results are incorrect.

The $(I'')^2R''$ loss in the armature can next be calcu-

lated by measuring the armature resistance when the machine is at normal running temperature, and knowing I'', the current corresponding to the load at which point the efficiency is being calculated.

The $(I''')^2R'''$ loss in the field can next be calculated, knowing R''' of the field winding and I''', the field current. The latter value can be measured by actually loading the alternator with the desired kind and amount of load, or better still, can be calculated as will be shown under the subject of regulation.

The $(I'''')^2R''''$ loss in brush contact can be calculated, knowing the field current and also that the contact resistance of carbon brushes on collector rings equals approximately 0.025 ohm at 40 amperes per square inch, approximately 0.038 at 20 amperes per square inch, and 0.045 at 10 amperes per square inch. If copper brushes are used, the brush contact resistance becomes negligible.

Now, as to the load losses. By "load losses" is meant the extra core loss due to the flow of current in the armature wires. This current induces in the neighboring iron, in the teeth, and in the wire itself, eddy currents and local hysteresis, which increase with the amount of the current.

This loss is measured by short-circuiting the alternator upon itself through an ammeter. Enough field current is put on the alternator to cause a certain desired current to flow in the short-circuited armature. With this current held as desired by the field control, a complete core loss curve is obtained just as is shown in Fig. 50, only in this case the curve includes the various I^2R values. Since the value of R is known it can be sub-

tracted, leaving the extra core loss due to the presence of the current in the armature wires.

To take this curve successfully, it is necessary to measure the resistance of the armature frequently, since the presence of the current tends to heat the armature and hence vary its resistance. Since the I^2R value is usually as great or greater than the short-circuited core loss itself, an error in the resistance R to be subtracted gives a large error in the result. It is customary to charge against the alternator 1-3 of this short-circuited core loss, since at best, measuring it as explained, with very low flux densities everywhere, a greater value undoubtedly results than when the alternator is actually operating with full flux in teeth, pole-pieces, and core. It may be regarded as a sort of semi-empirical value, more or less agreeing with actual conditions depending upon the details of design.

We know, now, all the losses, which are as follows:

1. The open-circuited core loss taken from the core loss curve at a voltage point equal to $E + I''R''$.

2. One-third the short-circuited core loss taken from the short-circuited core loss curve at the desired current.

3. $(I'')^2R''$ of armature.

4. $(I''')^2R'''$ of field.

5. $(I'''')^2R''''$ of brush contact.

6. Friction and windage.

The efficiency can therefore be calculated by dividing the output by the output plus the sum of these losses.

REGULATION OF AN ALTERNATOR AT VARIOUS POWER FACTORS.

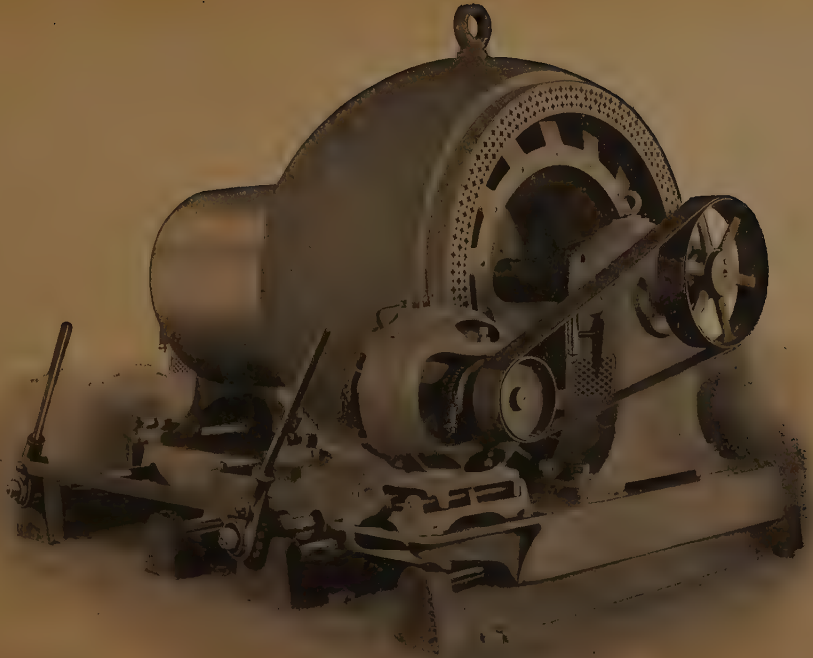
If an alternator is running at full load, and if this load be thrown off suddenly without allowing the speed of the alternator to vary, the voltage will rise to a value greater than before. This increase of voltage, divided by the normal voltage existing before the load was removed, is called the regulation of the alternator.

This rise of voltage can be directly measured if actual load can be placed upon the machine, and if means exist to keep the speed constant and at the desired amount. Under ordinary circumstances, however, these conditions do not exist. It then becomes necessary, and in fact is usually better, to take certain no-load readings from which can be accurately calculated the full-load regulation at any desired power factor.

Let us consider then, what causes the voltage of an alternator to lower when the load comes on. First, there is, of course, the ohmic-resistance drop of the winding. Second, there is the inductance of the winding located in the slots, which is equal to

$$\frac{\text{flux} \times \text{turns}}{\text{amperes} \times 10^8}$$

When the flux is thus produced locally around the wire, its path is across the air gap, across the pole face, back across the gap again, completing the circuit. This self-induction flux is, of course, an imaginary one, combining with the normal flux from the field winding, into the resultant flux, which actually flows through the coils



INDUCTIVE TYPE ALTERNATOR WARREN ELEC. CO.

of the armature, producing the total voltage $E + IR$, where R is the resistance of the armature, and I the current flowing. Thus, the core loss of an alternator giving the voltage E, corresponds to the flux necessary on no-load to produce the voltage $E + IR$.

The imaginary separate self-induction flux is in phase with the armature current, since all fluxes produced by current are equal in phase with their currents, and hence the electromotive force created by it is at right angles to the current. Thus, if the current of the armature is in phase with the electromotive force of the alternator, the electromotive force of self-induction would be combined at right angles with the electromotive force as shown in the diagram in Fig. 51.

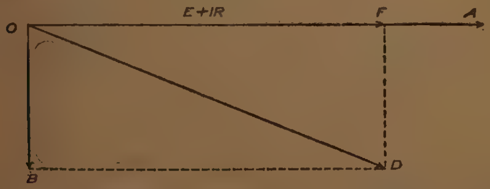


FIG. 51. DIAGRAM OF DIRECTION OF INDUCTIVE E. M. F. WHEN ARMATURE CURRENT AND E. M. F. ARE IN PHASE.

In the diagram, OA equals the current, OF equals $E + IR$, OB is the e. m. f. of self-induction, and OD the resultant e. m. f.

If the current in the armature lagged 90 degrees behind the e. m. f., the diagram would appear as in Fig. 52. Here, as before, OB is drawn 90 degrees from the cur-

rent OA, and OA is lagging 90 degrees behind the e. m. f. OF. The e. m. f. of self-induction, OB, exactly opposes, in this case, the external e. m. f.

Another cause of the voltage being lowered is armature reaction. This is a separate effect from the armature self-induction. Since current flows in the armature, the armature ampere-turns must act to create lines of force

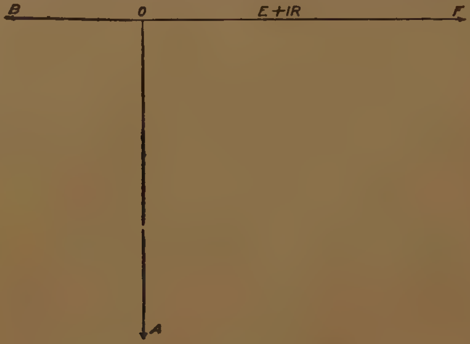


FIG. 52. DIRECTION OF INDUCTIVE E. M. F. WHEN ARMATURE CURRENT IS 90 DEGREES BEHIND E. M. F.

just as do the ampere-turns of the field. They are in the same magnetic circuit as are the field coils and must receive the same consideration. Thus, in every case for a given flux flowing through the armature and giving the voltage $E + IR$, the ampere-turns are the resultant of the field and armature ampere-turns.

Fig. 53 shows an alternator armature with the collector-rings tapped at A and B. The armature e. m. f.

reaches a maximum at the position shown. If the current is in phase with the armature e. m. f., the current reaches a maximum at the same position. The direction of magnetic action is therefore in this case represented by OC, at right angles to the direction of magnetic action of the field ampere-turns, shown by OD. The ampere-

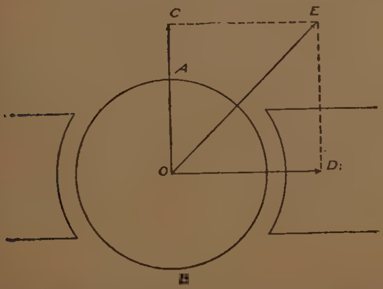


FIG. 53. DIAGRAM OF VALUE OF FIELD AMPERE TURNS WHEN ARMATURE CURRENT AND E. M. F. ARE IN PHASE.

turns in the field required to overcome this are shown by the resultant OE.

If, now, the current lags somewhat behind the e. m. f., the diagram appears as in Fig. 54. Here OC, the vector representing the current, is lagging the e. m. f. OA, and the resulting ampere-turns in the field required to overcome this is represented by the line OE, which is larger than before.

With the current lagging 90 degrees, the line OC would require additional ampere-turns in the field. Thus

as in self-induction, we have the armature ampere-turns acting at right angles at a non-inductive load and directly opposing at a 90-degree lagging load. On account of this similarity, C. P. Steinmetz has suggested combining the two effects, which he calls "synchronous impedance." This then becomes a value which can actually be measured upon any existing alternator. It is obtained as follows:

The alternator is short-circuited upon itself through an ammeter, just as in the case of a short-circuited core loss.

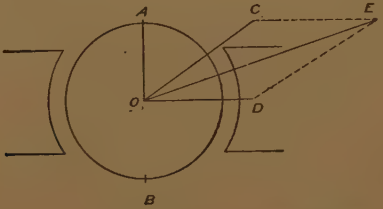


FIG. 54. VALUE OF FIELD AMPERE-TURNS WHEN ARMATURE CURRENT IS BEHIND E. M. F.

Enough field current is applied with the alternator running at normal speed to give any desired armature current, say a full-load current. Since the armature is more inductive than non-inductive, its current will lag practically 90 degrees behind the small induced electromotive force necessary to produce it on short-circuit. Thus the armature ampere-turns, as well as self-induction, directly oppose the field ampere-turns, or using the new expression, the field ampere-turns are a direct measure of the synchronous impedance.

We have now found a way to get this important value. When plotted the curve looks like that shown in Fig. 56, from which the ampere-turns of the field can be found for any desired number of armature amperes.

The next procedure in obtaining the regulation of an alternator, having now obtained the synchronous impedance, is to combine with its ampere-turns for any load

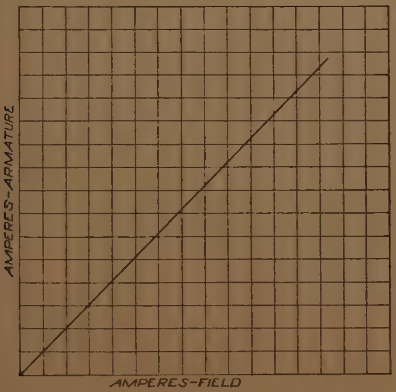


FIG. 56. SYCHRONOUS IMPEDANCE CURVE OF AN ALTERNATOR.

and electromotive forces the field ampere-turns to give the normal voltage plus *IR*. Hence, we wish a curve giving an open circuit and normal speed, the no-load terminal electromotive force plotted against the field ampere-turns. This curve is called a saturation curvo and is shown in Fig. 55.

The curve is taken with the residual magnetism removed, and with various increasing values of field current, the volts across the armature are read up to the point A. From A, the field current is gradually reduced till the point B is reached. An average of the rising and falling values may be used in calculation, though as

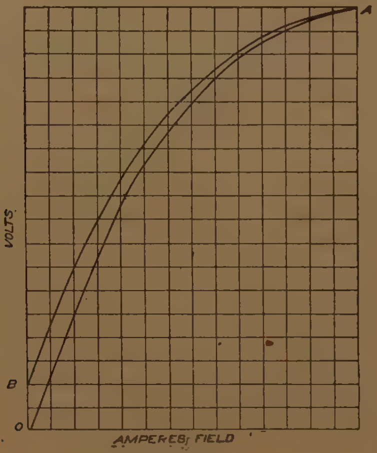


FIG. 55. SATURATION CURVE OF AN ALTERNATOR.

a matter of fact, these two curves are so near together that they are practically the same. The area OB represents the residual magnetism.

We now have at a given armature current the field ampere-turns for the synchronous impedance, and also for the no-load voltage plus IR. To obtain at this load

the total ampere-turns actually required by the alternator field, these two values are combined just as in the case of any reactance and electromotive force. It must be remembered that the synchronous impedance must be

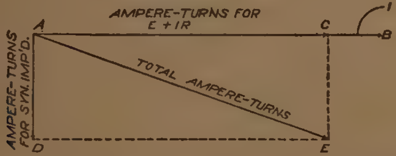


FIG. 57. DIAGRAM OF THE TOTAL AMPERE-TURNS REQUIRED BY THE ALTERNATOR FIELD ON A NON-INDUCTIVE LOAD.

plotted at right angles to the current. Thus on non-inductive load, the combination would be effected as in Fig. 57, giving the resultant ampere-turns equal to *AE*.

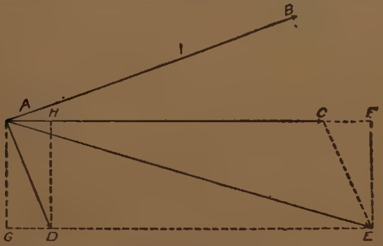


FIG. 58. DIAGRAM OF THE TOTAL AMPERE-TURNS REQUIRED BY THE ALTERNATOR FIELD ON AN INDUCTIVE LOAD.

For a lagging load, the diagram would be as in Fig. 58. When, as shown, the current *I*, or *AB*, lags behind

the e. m. f. AC by the angle BAC, the line AD, as before, being the synchronous impedance plotted at right angles to the current AB. Thus the resultant ampere-turns necessary are shown by the line AE, which is the diagonal of the two sides AC and AD, as before. By trigonometry, the length of AE, in Fig. 58, can be shown to have the following value:

$$AE = \sqrt{\left[(1-4)\cos a\right]^2 + \left[(E+IR)+(1-4)\sin a\right]^2}$$

The values of all the quantities on the right-hand side of the equation are known.

For any power factor, therefore, we have a method of finding the necessary ampere-turns to give the load at that power factor. If this load is thrown off and the field current be kept as before, the voltage will rise. The amount of the rise can be found from the saturation curve of the alternator shown in Fig. 55. If this voltage as read from the saturation curve be represented by E', and the terminal electromotive force at load by E, the regulation $= (E' - E) \div E$.

This method of no-load reading to calculate full-load regulation on ordinary normally designed commercial alternators, agrees exactly with the results obtained by throwing on and off load and observing the increase of voltage. It affords also an exact way of finding the regulation of an alternator of any size or phase without actually putting load upon it—a very necessary method con-

sidering the enormous size of individual units now being produced.

From the calculation of regulation, two curves can be plotted; one called a compounding curve, which gives for various loads and at constant speed the ampere-turns of field necessary to keep the alternator at a given voltage, and the other a curve showing the variation of voltage at a constant speed as the load comes on. Both these

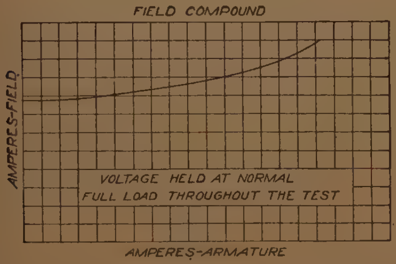


FIG. 59. COMPOUNDING CURVE OF AN ALTERNATOR.

curves can, without difficulty, be observed under actual running conditions if the necessary power, etc., is available.

The latter curve is of particular interest in showing how much the circuit voltage will be affected with varying load without field adjustment to keep the alternator at any desired voltage. The compounding curve of an alternator is shown in Fig. 59, and the drop of voltage curve or field characteristic is shown in Fig. 60.

TEMPERATURE MEASUREMENTS.

To obtain the temperatures of the various parts of a small alternator when operating under the conditions which may be met when permanently installed, it is only necessary to drive the machine at normal speed and at desired load until the temperatures become constant. This time on a 10-kilowatt machine may be 3 hours,

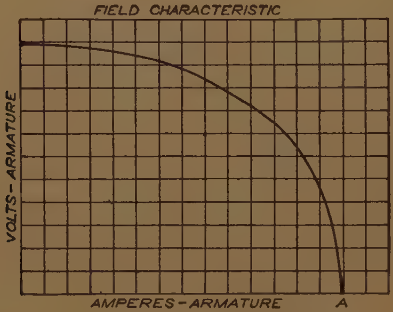


FIG. 60. FIELD CHARACTERISTIC CURVE OF AN ALTERNATOR.

With a 10,000-kilowatt alternator it is not usually possible to obtain the necessary power to turn the machine at full load.

There are two good methods of getting the data without actually supplying load. One method is to run the alternator free with enough field excitation to produce a core loss equal to the normal core loss of the machine

when running at normal voltage, that is, the core loss at $E + IR$ voltage on the core-loss curve taken, as has been described, plus the I^2R loss of the windings. The core then has within it the normal losses, and will rise in temperature accordingly; that is, the I^2R loss in the field winding may not be the same as when running under actual load conditions, but the rise can be obtained under the test conditions, and knowing also from the regulation test, as described, the full-load field curve, the new field temperature can be calculated from the no-load temperature, since rise in temperature is directly proportional to the watts lost in the spool.

The error is that the distribution of these losses is not the same as when running under load, but in ordinarily-designed machines, very satisfactory results can be obtained by this method, and its convenience and simplicity commend it.

Another method of obtaining normal full-load conditions in the core, is to oppose some spools to others and short-circuit the armature upon itself. If, for instance, an alternator having twenty poles, ten north and ten south, has them so connected that fourteen of them are north and six are south, and if full-field current be put upon the spools, there would be set up in the armature an electromotive force which would be the result of the free un-neutralized poles; in this case, eight poles would be left to produce electromotive force in the armature.

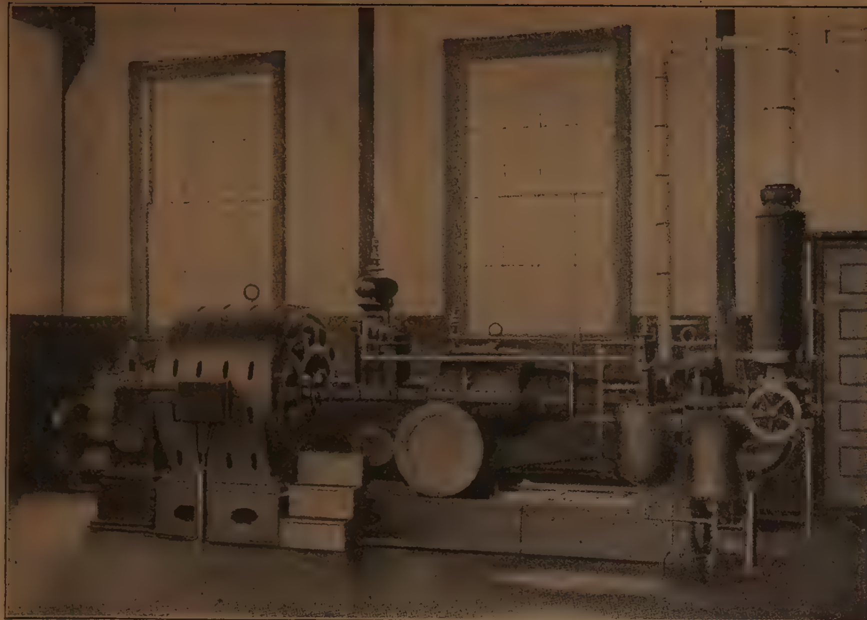
If, now, the synchronous impedance electromotive force taken as described with the armature short-circuited, requires just this amount of electromotive force, we have a method of producing full-load current in the

armature with full-load current in the field, and approximately normal core loss. Thus a certain number of poles are reversed against the others, the number being so chosen that the electromotive force resulting from their difference or resultant gives full-load current on the armature when it is short-circuited upon itself. Exact normal conditions are produced in this way, with the exception of the core loss.

It can be seen if one group of poles is reversed, that at the point of reversal two north poles will come together, and at the other end of the group two south poles. The percentage effect in an alternator of over ten poles is of small consequence, and for one of twenty poles entirely disappears. The method has the advantage of creating in the alternator normal stresses, for one part of the alternator acts as a motor under normal torque per pole, and the other part as a generator, so that pressure of coils against slots and end stresses exist during the run.

The method is extensively used by all manufacturers and gives accurate results. Knowing how to obtain regulation as has been described, the field current can be made to correspond to the load condition desired. The desired armature current is obtained by properly grouping the poles.

This method gives a measurement of field temperature and voltage under any of the desired load conditions, and thus covers the fourth item in the desired data. By means of the no-load open-circuit method, the field voltage for load condition may have to be calculated from the



WESTINGHOUSE TURBO-ALTERNATOR SET.

open-circuited test run condition. This, however, is a perfectly simple and accurate process.

WAVE TEST AT NO LOAD AND FULL LOAD.

This test is essential for many reasons. An alternator used for long-distance transmission and having a wave-shape departing seriously from a sine curve, has waves of higher frequency imposed upon the fundamental. This follows, because any wave is always the combination of one or more sine waves.

These waves of higher frequency acting upon the induction and capacity of the line may create a semi-resonant condition giving results entirely different from those predicted for the fundamental. Also, such waves acting upon induction motors may lower their efficiency, since all electromotive forces may no longer be 120 degrees apart, and since in a delta-connected induction motor for three-phase circuits, any other applied electromotive force will produce local currents in the winding, lowering efficiency, power factor, etc.

One method of taking such waves is to have a sector or contact piece, which can be accurately located with reference to the poles of the alternator. A brush revolves, touching this thin contact once in a revolution. The electromotive force is between this brush and the contact. When they touch, the circuit is completed to a voltmeter with a small condenser in multiple with it. Thus, the instantaneous voltage corresponding to the sector position is read. If the contact segment is moved in accordance with a scale calibrated in degrees, the wave form can be read off.

An excellent method of recording the wave form is by means of photography as employed in the oscillograph.

INSULATION RESISTANCE OF ALL WINDINGS.

This can easily be obtained by connecting to a given voltage a voltmeter in series with the insulation resistance desired.

ABILITY TO WITHSTAND A POTENTIAL GREATER THAN NORMAL.

Of more importance than the insulation resistance is the ability of the windings to withstand from two to three times the electric stress to which they are ordinarily subjected in normal operation. It is proper to apply such a potential for one minute. For instance, a 500-volt railway generator ought to be able to withstand 3,500 volts between windings and the iron of the machine for one minute with the machine at normal running temperature. An alternator of 2,300 volts should withstand 9,000 volts. The American Institute of Electrical Engineers has issued a formal statement of the best present practice regarding insulation tests. It is necessary to apply the potential when the machine is hot, as then the usual insulation is less able to withstand the strain.

NOISE OF OPERATION.

For obvious reasons, the noise of operation is objectionable. A properly designed alternator need not make noise of any consequence. Noise may be due to loose laminations, in which event it is not objectionable, but the loose laminations may injure the machine since their movement may wear into the insulation or may break off

the teeth of the core. To correct the trouble, the core must be stiffened up.

Noise may be due to excessive magnetic densities in the teeth of the core, pole influence, or to mechanical puffs of air giving a whistling noise. The air and magnetic efforts usually produce similar sounds, so that rotating the armature at normal speed with field off must be tried to find the true cause.

QUALITY OF INSULATION USED.

While this is not essentially a testing point, a purchaser ought to know the kind of insulation in his machine. Various insulating materials exist which may serve temporarily and be all right when cold, but only the properly made varnishes with linseed oil as base will be just as good at temperatures which an alternator may have to withstand, and will improve rather than grow worse with age. For windings designed to carry high potentials, a statement of the kind of insulation used should be a part of the acceptance test.

METHODS USED TO APPLY INSULATION AND TO WIND COILS.

As the quality of insulation is important, so also are the methods of applying it and of winding the coils. Coils can be wound and insulated in the form in which they should be when applied to the alternator armature, and then located in their final position without hammering, or they can be only approximately formed and not wholly insulated, and then forced by pressure or hammering into their final position. The former method costs more, but leaves a coil in position with all its insulation perfect.

The latter method is cheaper, and gives for the first test, perhaps, as good insulation resistance and ability to withstand the American Institute of Electrical Engineers' "high potential" test, but the life is not there, and at the end of 20 years the two machines are greatly different in value.

ABILITY TO STAND EXCESS OF SPEED.

Since various conditions may arise where alternators may run up above normal speed, the complete test of a machine should include this performance. Many alternators which are to be connected to water-wheels are required to operate at double speed in case of a runaway due to governor troubles.

SATISFACTORY OPERATION OF BEARINGS.

This is an essential feature in the satisfactory operation of a machine. Bearings should run with a rise in temperature of less than 40 degrees Centigrade; otherwise, extra heating, due to temporary dirt may run the temperature up to a point when the melting of babbitt or cutting may occur with consequent need of an actual shut-down.

Bearings should not leak or throw oil.

Oil, particularly that of the cheaper varieties, eventually injures insulation. It permits the sticking of dirt to leakage surfaces, which when dry or clean should serve as insulation. The result is that in time a ground will occur and a short-circuit result. There is no excuse under any condition for the leaking or throwing of oil from a bearing.

ROTATION OF PHASE.

A given induction motor should run in a certain definite direction when connected similarly to all alternators of a given company's make. Thus, such alternators, when connected in multiple a certain way, will go all right, and when an induction motor load is thrown from one alternator to another, a reversal of the motors will not occur. A testing room should, therefore, have a phase rotation "judge" applied to every alternator shipped. The "judge" consists of an induction motor always used for this purpose.

SATISFACTORY MECHANICAL DETAILS.

The mechanical details are too many to be mentioned here, but such features as the following should all be examined and properly passed upon: Ease of assembly, and ability to get at parts that might need repairs, size and uniformity of air gap, capacity of oil well for bearings, kind of oil rings, quality of material, arrangement for keeping the case tight, material used to insulate armature laminations from each other, pressure fits, size of shaft, mechanical holdings of spools, holding of coils in slots, free longitudinal motion, or end-play of shaft in bearings with and without field, "springing" of field with excess of magnetism, strength of fingers to hold teeth of armature tight, strength of core, and direction of air ventilating currents.

ABILITY TO WITHSTAND SHORT-CIRCUIT.

To properly understand the action of an alternator when short-circuited, the following should be appreciated and understood:

1. The time constant of any circuit and its influence on the rise or fall of current in that circuit—Lenz's law.

2. The armature reaction of an alternator.

3. The self-induction of an alternator.

4. The current in an alternator armature when the latter is short-circuited and the field gradually brought up to normal value.

TIME CONSTANT.

The time constant of a circuit is expressed by the formula $\frac{L}{R}$, where L is the coefficient of self-induction and R is the resistance of the circuit. The coefficient of self-induction of a circuit equals (maximum flux passing through that circuit $\times$ the number of turns surrounding that flux) divided by (amperes flowing in the circuit $\times 10^8$). The unit of self-induction is the henry. The self-induction is calculated as shown, which thus gives henrys; when multiplied by $2\pi\ n$, where n is the frequency, the product gives the inductive resistance in ohms. Thus in any circuit, knowing the flux passing through, the turns, the current producing the flux, and the resistance, the value of $\frac{L}{R}$ can be calculated.

Self-induction in an alternating circuit, or in a circuit in which the current varies, shows itself as a back e. m. f. Thus, if the current in a circuit is growing smaller, the lines of force in that circuit are decreasing. If in any circuit the lines of force are decreasing, there is induced an e. m. f. in such a direction as to produce a current

which tends to create lines of force as originally passing through. Thus the current induced by this decrease of lines of force tends to retard the reduction of flux, as well as the reduction of current in that circuit.

This can be seen by referring to Fig. 61. Let the current flow in the circuit *A* in the direction 1-2-3-4

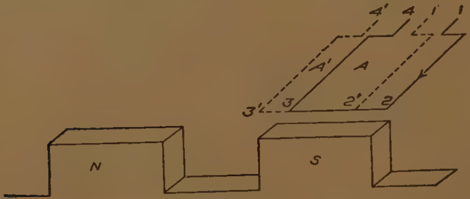


FIG. 61. DIAGRAM TO ILLUSTRATE THE ACTION OF SELF-INDUCTION.

shown by the arrow. The lines of force flow up from the *N* pole and down into the *S* pole. Let the current start to decrease. By this action there is induced a current tending to flow clockwise or in the direction as before. This follows from the well-known law that looking at any circuit along the lines of force, that is, in the direction a free north pole would tend to move, a reduction of the lines of force produces an e. m. f. tending to create current in a clockwise direction. An increase in the lines of force produces opposite results. This, in turn, is of course, based on the fact that a wire moved to cut lines of force has created in it an e. m. f. in a certain definite direction.

Thus it will be seen that the extra induced current is

in the same direction as the original current and tends to keep it from decreasing. Suppose just opposite this circuit there is located another circuit A', short-circuited upon itself. Let us see what occurs when the current in A commences to decrease. The lines of force which are created by the current in A, and which pass through the circuit A', now start to decrease. As before, this decrease creates an e. m. f. in A', sending the current around clockwise in the direction of $1'$-$2'$-$3'$-$4'$.

This current tends to send lines of force in the same direction as the current in A (which is now being decreased) originally did. Thus the act of reducing the current in A and the flux produced by it has created a current in A which tends to hold up this original flux. This has been expressed as Lenz's law, that in all cases of magnetic induction the induced currents have such a direction that their reaction tends to stop the motion which produces them.

It can be shown that this value $\frac{L}{R}$ expresses in seconds approximately two-thirds of the interval which elapses from the time of applying voltage to a circuit to the time when the current has reached its constant value, or $\frac{E}{R}$, E being the applied e. m. f. (a constant) and R the resistance of the circuit. As has been explained, this rise of current cannot be instantaneous, but the back e. m. f. due to the increase must first be overcome, using up a certain definite amount of time.

The formula for this increase of current is:

$$I = I_1\left[I - E^{-\frac{tR}{L}}\right]$$

I = current in amperes at any instant t.
I_1 = final current.
E = the base of the Napierian logarithm = 2.71828.
R = resistance of the circuit in ohms.
R_1 = internal resistance of circuit.
L = inductance in henrys.

A curve plotted by introducing values in this formula is shown in Fig. 62.

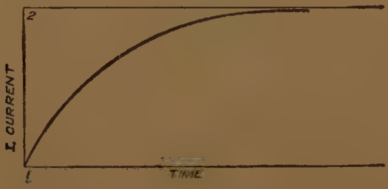


FIG. 62. METHOD OF INCREASE OF CURRENT IN AN INDUCTIVE CIRCUIT.

The formula for the fall of current in a circuit closed by the resistance R at the instant the voltage is withdrawn is:

$$I = I_1\, E^{\frac{-R+R^1}{L}t}$$

A curve plotted from values abtained by this formula is shown in Fig. 63.

ARMATURE REACTION.

In considering the armature reaction of an alternator, let us study Fig. 64, representing an alternator. At the

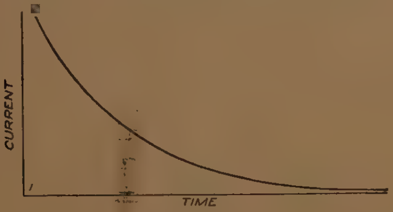


FIG. 63. DYING OUT OF CURRENT IN AN INDUCTIVE CIRCUIT.

position shown the e. m. f. in the armature is always a maximum. At a position 90 electrical degrees from this the e. m. f. is zero. If the current is in phase with e. m.

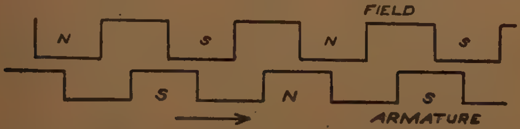


FIG. 64. ALTERNATOR FIELD AND ARMATURE CORES HALF OPPOSED; ARMATURE E. M. F. MAXIMUM.

f. when the latter is a maximum, the former is also a maximum.

Since the current in the armature passing through the armature turns creates a magneto-motive force precisely as do the field ampere-turns, they must be reckoned with as doing their part in creating the flux

through the armature, as well as the field ampere-turns. When the current is a maximum, as shown in the position in the figure, the ampere-turns of the armature are acting at right angles to the field ampere-turns. The tendency is thus to distort the field, the flux growing denser at the pole tips 4 and 3 and weaker at 5 and 6. The effect of this action is to require more field ampere-turns, since the extra turns required by the dense tips are more than the less turns required by the weaker tips.

If, however, the current lags behind the e. m. f., it does not reach a maximum until the armature has passed beyond the position shown in Fig. 64. The current may be a maximum at the position shown in Fig. 65. In this

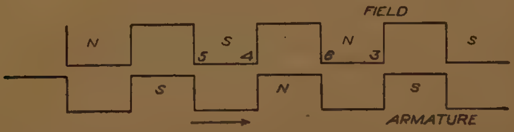


FIG. 65. FIELD AND ARMATURE CORES NOT OPPOSED.

case the armature ampere-turns exert a demagnetizing effect, as well as a cross magnetizing effect, and hence the extra current in the field coils are required to overcome these. If the current lags 90 degrees, all the turns of the armature oppose those of the field. Thus the voltage of an alternator is the resultant of the ampere-turns of the field and the armature, the latter, or lagging, currents tending to pull down the voltage, requiring extra ampere-turns in the field to make up.

SELF-INDUCTION.

The effect of self-induction in an alternator is entirely different from that of the armature reaction just described. The former is a question of ampere-turns of the armature, and their influence on the total ampere-turns producing the flux, and hence the e. m. f. The self-induction of an alternator is the back e. m. f. created by the local flux around the wires of the armature proper.

Thus, in Fig. 66 *W* indicates two wires in the slot of an armature core which is opposite the pole *N*.

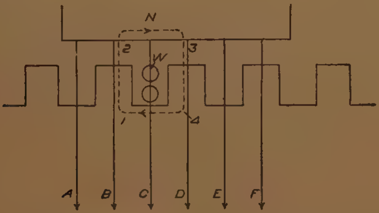


FIG. 66. DIRECTIONS OF FIELD AND ARMATURE FLUX.

From this pole are streaming into the core the lines of force or flux represented by the arrows *A, B, C, D, E, F*. This is the main flux producing the generator e. m. f. and is the flux which results from the field ampere-turns and the armature reaction or armature ampere-turns described in the foregoing.

There is, however, another flux circulating around the wires *W* in the slot, which does not produce an e. m. f. as does the flux *A, B, C, D, E, F*, but holds down the e. m. f. of the machine. The path of this flux is shown by

the dotted line 1-2-3-4, circulating around the wires, is small compared with the main flux of the machine. The time constant $\frac{L'}{R}$ of the lesser flux is far smaller than the time constant $\frac{L}{R}$ of the main flux, for L' in the one case equals (self-induction flux $\times$ armature turns) divided by (amperes $\times$ 10^8), and in the other L equals (main flux $\times$ turns in spools) divided by (amperes $\times$ 10^8).

Let us take a specific case of a 100-kilowatt, single-phase alternator of twenty poles and 500 volts.

Flux per pole = say, 6,000,000 lines.

Turns per spool = 600.

Amperes per spool = 6.

Resistance of twenty spools in series = 12 ohms.

$$\text{Then } \frac{L}{R} = \frac{6{,}000{,}000 \times 20 \times 600}{100{,}000{,}000 \times 6 \times 12} = 10$$

Suppose the armature to have twenty slots per pole and two conductors per slot, and carry a current of 200 amperes. The self-induction flux of this current would be 60,000. The resistance is 0.15 ohm. Then

$$\frac{L'}{R} = \frac{60{,}000 \times 20 \times 2 \times 20}{100{,}000{,}000 \times 200 \times 0.15} = 0.016.$$

Thus the time to bring up the main flux after suddenly impressing an e. m. f. on the spools is much greater

the time for the rise of the self-induction flux; or equally, the time for the main flux to die out, the e. m. f. creating it having been removed, is very much greater than the time for the self-induction flux to die out under similar conditions.

SHORT-CIRCUITING THE ALTERNATOR WITH INCREASING FIELD.

Let us take a three-phase alternator and without any field current short-circuit all phases of the armature simultaneously. Now gradually bring up the field current. As this is done, the current in the armature will gradually increase until it reaches a value perhaps three times the normal, when the field has reached its normal running full-load value. Of course, at this point there are no armature volts, since the terminals are all connected together, forming a short circuit.

The field current is steady. The armature currents combine to produce a magnetomotive force of constant value (not varying with the wave of current), which is characteristic of a polyphase armature winding, as can be shown. The ampere-turns of the field equal approximately those of the armature, the latter currents lagging so as to directly demagnetize the field ampere-turns. We thus have a stable condition, as described.

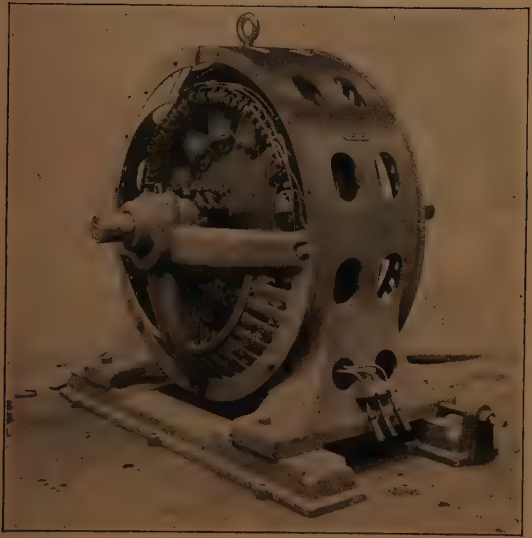
If only one phase be short-circuited, the armature reaction is no longer constant, but pulsating, so that while a stable condition exists the field current no longer is wholly constant, since the flux resulting from both armature and field ampere-turns varies, the field current being constant and the armature pulsating with respect

to the field. This flux varying, as described, and passing through the field turns, creates in them an e. m. f. affecting the field current itself. Eddy currents are also created in the pole face, particularly if the pole is not laminated, and tend, according to Lenz's law, to stop the variation.

Let us now apply the previous data to the conditions resulting from short-circuiting an alternator suddenly upon itself when running with normal field current. Let us consider first a three-phase alternator which suddenly has all three terminals short-circuited at the terminal board, as if the cable leading from the machine suddenly short-circuited at this point while the machine was fully excited.

The short-circuit may occur at the maximum point of e. m. f. or at some other point. The results are apparently not much different, for what the first e. m. f. wave does not do the next one does. But we will consider for a moment that the short-circuit occurs first at the maximum of the e. m. f. wave of one of the circuits. In that circuit there is a rush of current and an endeavor to fulfill Ohm's law, that is, to reach a current $\frac{E}{R}$ when E equals the e. m. f. at the moment chosen and $R =$ the resistance of the armature (we assume that the external circuit has no impedance).

But this cannot occur immediately. The flux of self-induction must be created as the current rises. The time constant of this self-induction circuit described



WESTERN ELECTRIC CO. THREE-PHASE GENERATOR.

previously must be satisfied. Thus the speed of this rise is such that $\frac{L'}{R}$ of the self-induction circuit will be satisfied. As a matter of fact, the speed is nearly instantaneous, the current jumping to many times the normal value. All this holds true of the other phases of the alternator.

As stated, the armature reaction or magnetizing effect of a polyphase alternator is a constant value, the summation of the armature magneto forces of the various phases always being a constant at any given output of current. Thus the first tendency of this suddenly rising armature current is to act upon the voltage and flux of the machine, since the armature furnishes ampere-turns just as important as the field.

Also on a short-circuit, since the inductance of the winding is much greater than the resistance, the phase of the current resulting from this short-circuit is one giving a large lagging effect. Hence this current, as has been shown, is a direct demagnetizing one. Thus this rush of current tends to immediately pull down the flux and the voltage of the alternator to practically zero. While this is accomplished eventually, to be sure, it is not accomplished at once, as will be shown.

Eventually, it is true, this armature current reaches a certain value, the voltage of the armature becoming zero. The flux of the machine becomes practically zero, only enough being left to create an e. m. f. necessary to force the armature current through the armature impedance (a very small amount of flux). The field and arm-

ature ampere-turns are practically equal and directly opposed.

While all this occurs immediately, as far as the eye can see, as a matter of fact it is done only after the time constant of the main flux is satisfied. For when this armature current jumps up, so also does the field current by an equal amount (expressed in ampere-turns).

When the armature current on its first leap has reached its greatest value (perhaps twenty times its eventual constant value), the field current has also leaped to many times its normal value, and, for a moment, the flux is held up by this leap of field current. Thus the $\frac{L}{R}$ of the main field flux comes in and the leap of field and armature current dies down, in accordance with the curve shown in Fig. 63. The high armature current holds on, creating an enormous current, and only letting go gradually, in accordance with the law expressed by the curve. The flux declines to zero, the leap of the armature current declines to the value described in section 4, and the leap of the field current returns to its old value.

A plot of these conditions might, therefore, look like Fig. 67. The curve *GCD* shows the variation of flux, being constant up to the time *B*, where the short-circuit occurs, then declining to zero, in accordance with the time-constant law.

Curve *HJE* shows the armature current, which is zero or any usual running value, up to the time *B*,

then jumping to *J*, following the time-constant law of the inductance flux (we assume that the field circuit has no inductance, either in the spools or in the external field

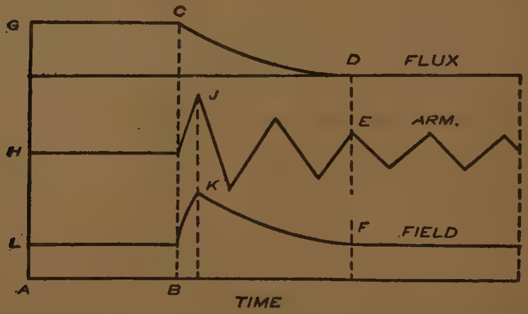


FIG. 67. RELATIONS OF FLUX, ARMATURE AND FIELD CURRENT REACTIONS ON SHORT-CIRCUIT.

circuit, as otherwise this inductance should be considered as part of the armature self-inductance in considering the original leap of current) and then declining to the value *E*, which is the short-circuit current with normal field after the rush is over.

Curve *LKF* shows the action of the field current. At the time *B* of the short-circuit this current leaps up to *K*, holding the flux constant for a moment. It then declines like the rest till normal value is again reached at *F*. If only one phase is short-circuited, all this occurs as before; but now, as has been explained, the field current is no longer a smooth curve. It then might appear as in Fig. 68. The jump occurs at *a-b*, as before, and the

tops of the current grow less and less to a final value. An illustration of this from actual readings taken while

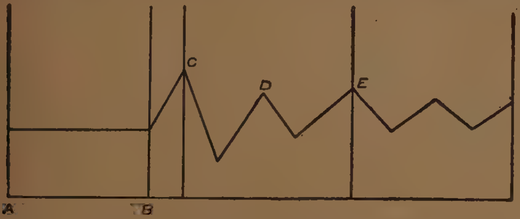


FIG. 68. ACTION OF FIELD CURRENT WITH ONE PHASE SHORT-CIRCUITED.

a short-circuit was occurring on one phase is shown in Fig. 69.

The instrument used was so sensitive and active as

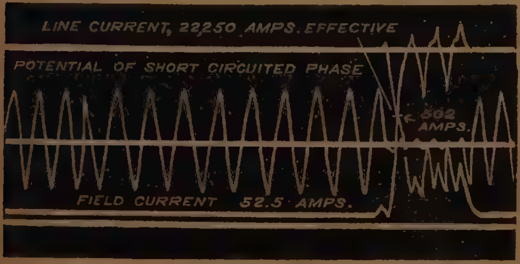


FIG. 69. OSCILLOGRAPH RECORD OF THE RESULTS OF A SHORT-CIRCUIT IN AN ALTERNATOR.

to actually plot the wave of e. m. f. or current itself (ordinary commercial instruments simply record the

square root of mean square values). An examination of the illustration shows the jump of armature current, the tops of the waves growing less and less. The jump of field current is also shown. The curve is not continued down to the final value, since the switch used to make the short-circuit was automatically opened again, restoring the original condition.

As the figure shows, the field current was running along at 52½ amperes when the short-circuit was applied. The current then jumped to 502 amperes and started to decrease, in accordance with the curve shown in Fig. 63, thus making less and less the tops of the current waves. These current waves of the field were produced mutually by the tremendous alternating "armature reaction" ampere-turns (plus the field ampere-turns) and the jump and decline of a direct current.

Thus, as is shown, the decline is that of a diminishing direct current superimposed upon an alternating one, the former being an almost instantaneous jump in a certain direction and then a decline, the latter being due to the field flux variation, and hence a variation of the field current itself (the field current being completed through the exciter armature), resulting from a direct current in the field and a tremendous alternating current in the armature acting together in the same magnetic circuit.

The voltage, as shown in the middle of the figure, goes to zero at the time of the short-circuit (or practically so, the variation being due to the existence of a slight resistance of the cable making the short-circuit), and rises again when it is over. The line current jumps

to a very large figure—22,250 amperes—and dies down just as described in connection with the field, that is, there is superimposed upon the alternating current a large decreasing direct current, producing the diminishing maximums below the line in the figure which marks the normal line current.

Even during the time of this short-circuit the decrease of these maximums and the approach to an alternating current symmetrical about the line marking the normal line current is very plain in the figure.

During this transient interval with normal flux part of the time and with enormous armature currents the torque or pull on the armature windings is tremendous. The effect upon a machine is as if it had been struck with a thousand hammers.

While a properly designed machine will stand this performance repeatedly without trouble, special precautions in design must be taken to withstand it. The windings which project beyond the core, and which are thus not supported by the slots in the core, unless held firmly by bands inside and out, or unless they are of unusual strength themselves, will be distorted entirely out of shape, thus ruining the winding. In addition, the arms of the revolving element, the keys in the shaft, and the shaft itself all undergo an enormous strain, so that good alternator design means a consideration of mechanical forces far beyond those connected with normal operation. With direct-current apparatus, there is an automatic relief in the fact that the machine will "flash over" at the brushes, relieving the strain to a certain extent.

CHAPTER XIII.—TESTING INDUCTION MOTORS.

AN INDUCTION motor field or stator is usually wound either three-phase or quarter-phase. The armature or rotor may be wound similarly, or may have no definite winding, consisting simply of single bars located in the slots and connected on the ends with a conducting ring.

The latter kind of winding is the well-known "squirrel-cage," and is used very extensively where an especially low starting current is not essential. It is a cheaper and more rugged form of winding, and, after the motor is once started, gives as excellent results as the direct-wound winding. This type has a starting resistance connected with it which is left in at starting and gradually cut out as the motor comes to synchronism.

The squirrel-cage type of motor is started with a compensator which gives a low voltage at the time of starting, and then increases the voltage to normal after the speed increases to such a value that the back e. m. f. within the armature takes the place of the starting resistance. It is a fact that for a given weight of copper on the rotor it makes no material difference in regard to the characteristics of the motor, whether the winding is a direct phase winding, like the stator, or whether it is a squirrel-cage winding, and, therefore the items mentioned herewith as necessary to have in order to properly

understand a given motor apply both for the direct winding and for a squirrel-cage winding.

The only exception in the methods of test in the two cases is in the torque curves from rest to synchronism. With a direct winding with its starting resistance connected to it, the torque from rest to synchronism should be taken with the various resistances in circuit, and one of the resistances should be so chosen that the maximum torque would occur just at the starting point.

It is a fact that the insertion of resistance in a rotor of an induction motor has no influence on the maximum torque. It only regulates the drop in speed at which the maximum torque occurs. Therefore, a resistance may be chosen which will give the maximum starting torque at rest. In a squirrel-cage rotor having no starting resistance, the starting torque naturally will be low, as will the torque in the first part of the rise of speed toward synchronism, since without resistance the rotor current phase is lagging at starting, as then the rotor has within it full frequency and much more inductance than resistance. The low torque per ampere on the squirrel-cage at starting is made up by putting in more amperes, and these extra amperes required at starting by the squirrel-cage are obtained not directly from the line, but, as stated, through a compensator, which thus relieves the line (the ratio of the compensator is, perhaps, 2 to 1) from the large drain of current.

Thus, items 1 to 9, mentioned hereafter, concerning induction motors, are required similarly for the direct-wound rotor as well as for the squirrel-cage winding. The currents in a properly constructed squirrel-cage

GENERAL ELECTRIC ROTARY CONVERTER FOR HIGH VOLTAGE TRANSMISSION LINES.

circulate around in phase electrically, acting similarly to the currents in a direct winding.

The mechanical and electrical characteristics in an induction motor of importance to a customer, and of course to a manufacturer, are as follows:

1. Efficiency at various loads.
2. Power factors at various loads.
3. Apparent efficiency at various loads.
4. Maximum output at normal voltage.
5. Current and torque at starting.
6. The "running light" current.
7. The torque from rest to synchronism.
8. Drop in speed at various loads.
9. Temperature of the various parts under normal load until constant temperature is reached; also temperature after overloads of certain amounts and after certain times.

Items 1 to 9 can be obtained by applying to the motor the well-known prony brake, reading the output with it and input with wattmeters and ammeters. This prony brake for the torque readings should be not the ordinary one, but a revised prony brake method should be used. The motor rests on a platform scale, and the change of its weight read as the pull from the torque occurs, gives a measure of the torque. Such an arrangement permits an accurate reading at any part of the curve from rest to synchronism, the man operating the brake holding the motor at any desired per cent synchronism by the tension on the cord or tape around the pulley producing the torque. For the heat run it is more convenient to belt a double-current generator as load,

the energy going into a rheostat or being "pumped back" into the source of energy, similar to the "Hopkinson" method in double-current apparatus. With a three-phase motor, two wattmeters are necessary, the current coil of No. 1 wattmeter being in line No. 1, the current coil of wattmeter No. 2 in line No. 2, the voltage coil of wattmeter No. 1 between line No. 1 and No. 3, and the voltage coil of wattmeter No. 2 between line No. 2 and line No. 3, Fig. 70.

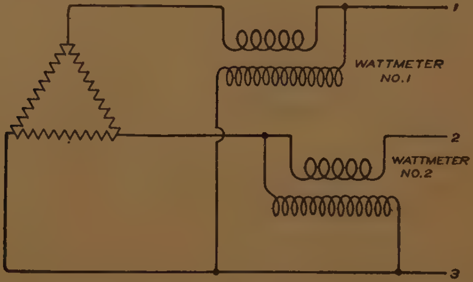


FIG. 70. CONNECTIONS FOR HEAT TEST OF THREE-PHASE INDUCTION MOTOR.

The watts input equals the sum of the two wattmeter readings. It must be remembered, however, that under some conditions, if the lag of the current behind the e. m. f. is over 60 degrees, one wattmeter will read negative. The reason that the wattmeter reads negative is that the current *C*, in line No. 1, for instance, if it were inductive, differs in phase from the voltage between 1-3 by 30 degrees, which is true of any three-phase circuit,

Fig. 71. If the current in line 1 commences to lag, the angle formed with the voltage 1-3 will commence to increase, while the angle of current in line 2 with volts 2-3 will commence to decrease. When the lag is 30 degrees, *C′*, the current in line 1 is out of phase 60 degrees with voltage 1-3. When the current in line 1 is lagging 60

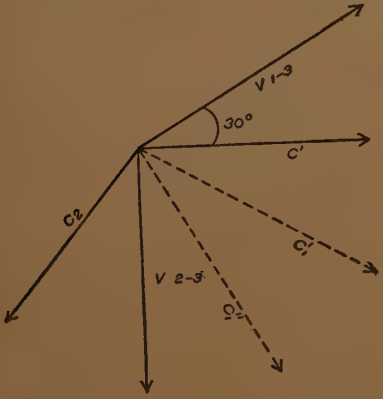


FIG. 71. RELATION OF CURRENT AND VOLTAGE WHICH GIVES NEGATIVE WATTMETER READING.

degrees, *C″*, it becomes 90 degrees out of phase with 1-3, and thus the wattmeter reads 0. With any further lagging of the current the wattmeter will read negative.

As a matter of fact, in many cases in induction motors at no load this 60 degrees or more lag actually does occur and a negative reading appears in one wattmeter. The reason the other wattmeter does not read

negative is that if the current in line 1 gets more and more out of phase with the voltage 1-3, it follows, in any three-phase circuit, that the current in line 2 gets more and more in phase with voltage 2-3.

The current in an induction motor lags in phase behind the applied e. m. f., due to the magnetizing component of the entering current (a true magnetizing current, it is well known, always lags just 90 degrees behind the e. m. f. producing it). The apparent input found by multiplying volts and amperes is greater than the real input shown by the wattmeters (in a three-phase motor, the apparent input equals the amperes per line multiplied by the volts between the lines multiplied by the square root of 3).

The ratio between the real and apparent input is the power factor, equal to the cosine of the angle of lag of the entering current. The ratio of the real output to the apparent input is the apparent efficiency, and the ratio of the real output to the real input is the real efficiency. Thus all these values can be measured as described.

The maximum output can also be found. An induction motor will take increasing load with decreasing speed until a point is reached when it will carry no more and will stop unless the load is reduced. The product of flux entering the armature and the ampere-turns of the armature at this point commence to decrease.

The prony brake method serves well up to about 75 horsepower. Above this, owing to various difficulties, it is not always practicable to actually load a motor and measure its output directly. There is a way, however,

to measure certain values and calculate the rest. No attempt will be made here to prove the formulas used, but the method of applying them will be described.*

The three measurements necessary to calculate these values are as follows:

1. The excitation or running light current, reading at the same time the watts input. This data can best be taken from a curve, such as is shown in Fig. 72.

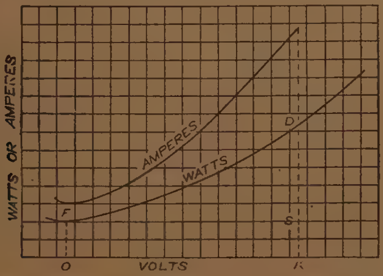


FIG. 72. EXCITATION CURVES OF AN INDUCTION MOTOR.

2. The impedance reading, which is the reading of current input, taken at the same time as the watts input, with the motor standing still. This is shown in Fig. 73.

3. The drop of speed or slip of armature at any definite current input.

From these three readings, together with the resistance of the stator at normal temperature, all the load values of any induction motor can be calculated.

*For complete proof (without calculus), the reader is referred to the chapter on induction motors, in the author's book on "Alternating-Current Engineering."

The friction and core losses may be obtained from Fig. 72. The friction is the value of the watts at F, allowance being made for I^2R loss during the taking of this curve. The core loss equals the reading at D, minus that at F.

The I^2R loss of the windings may be read directly from the curves in Fig. 73, at the current desired. The

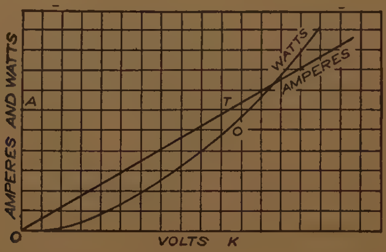


FIG. 73. IMPEDENCE CURVES OF AN INDUCTION MOTOR.

curve gives the sum of the field and armature I^2R, and, subtracting the I^2R of the field, the I^2R of the armature is given.

To obtain the power factor and efficiency at any load, the following equation is used:

$$H.P. = \frac{p R_1 E_0^2 S(1-S)}{746\left[(R_1 + S R_0)^2 + S^2(2\pi n L_1 + 2\pi n L_0)^2\right]}$$

p = number of circuits (three for three-phase).
n = cycles in stator.
R_1 = resistance of secondary circuit.

E_0 = voltage applied to one circuit.

S = slip (1 at standstill, 4 at 4 per cent drop in speed).

R_0 = resistance per circuit of primary.

We now show how to find the various values in this formula, which, when inserted, permit the calculation of the horsepower. Inserting various values of the slip with the other values which simultaneously go with it, the complete curve of horsepower can be plotted. If the slip is actually measured for a given input, the horsepower output for this input is calculated by the formula above, and thus the complete curve, horsepower, slip, current input, power factor and efficiencies can be calculated and plotted.

If the input of current for a given slip is not measured, it must be calculated as shown in the formlas later on. We will first assume that the slip is read for a given ampere input, and that the horsepower is to be calculated from the formula above at this slip and input, which thus gives the ratio between output and input for efficiency, and output and apparent input for apparent efficiency and power factor.

If $2\pi nL_1 = X_1$, and $2\pi nL_0 = X_0$, then, at the current chosen from Fig. 73, we have:

$$\text{Current} = \frac{\text{volts}}{\sqrt{(R_0 + R_1)^2 + (X_0 + X_1)^2}}$$

This formula gives us the value of $2\pi nL_1 + 2\pi nL_0$ for the formula of horsepower above. Since the current and the volts are read and the sum of the resistances can be calculated at any point on Fig. 73, and since the watts

read with this curve as taken give the sum of I^2R of both stator and rotor (the core loss being negligible under these conditions), and since I is known, the sum of $R_0 + R_1$ is known for any given stator current; thus $2\pi nL_1 + 2\pi nL_0$ can be calculated.

The quantities on the right-hand side of this equation are all known except R_1. This is calculated from the three following equations:

$$E = \frac{E_0 R_1}{\sqrt{R_1^2 + 2 R_1 S R_0}}$$

$$I_1^2 R_1 = a$$

$$I_1 = \frac{S E}{R_1}$$

Here E equals the back e. m. f. in the windings, due to motor flux.

These three equations can be used to solve for I_1 or R_1. Thus in the formulas for horsepower, at any current input for which the slip S is measured, all values are known, and thus the amperes input, slip, horsepower output, and hence efficiency, power factor, and apparent efficiency can be obtained.

If, however, the slip is measured at only one current input, and if it is used only to calculate R_1, as shown, the primary current for any horsepower and any other slip can be found from the formula:

$$I_0 = \sqrt{I^2_{00} + \left(I_{11} + \frac{S E}{R_1}\right)^2}$$

I_0 = primary current.

I_{00} = exciting current.

I_{11} = energy component of exciting current.

At normal voltage exciting current is read and $= I_{00}$.

Core loss $= K$ (as found in Fig. 72). Then $\frac{K}{p}$ = core loss per circuit. Hence energy component $= \frac{K}{pE} = I_{11}$.

E = back e. m. f. per circuit produced by the motor flux.

R_1 = secondary resistance.

S = slip.

$$E = \frac{E_0 R_1}{\sqrt{R_1^2 + 2 R_1 S R_0}}$$

Hence the three readings, one running light, with wattmeters and ammeters, one standing still, with wattmeters and ammeters, and one slip reading with simultaneous entering primary current, permit the calculation of all values of any induction motor of any size.

The maximum output equals

$$\frac{p E_0^2}{1492 \left[(R_1 + R_0) + \sqrt{(R_1 + R_0)^2 + (X_1 + X_0)^2}\right]}$$

All these terms have been deduced, as shown, for calculating the horsepower.

The starting torque in pounds at one foot radius equals

$$\frac{S E_0^2 p b R_1}{17.04\, n \left[(R_1 + S R_0)^2 + S_2 (2 \pi n L_1 + 2 \pi n L_0)^2\right]}$$

n = cycles per second in primary.
b = number of poles in motor.
The remaining terms are the same as before.

TEMPERATURE OF THE VARIOUS PARTS.

These should be obtained by actual running, since there is no convenient way of using a no-load method on an induction motor, although full-load temperatures may be deduced from the no-load values, as explained for generators. Particular attention should be given to short-circuited coils. They will not burn out like coils on a direct-current machine, but will take about three times normal current and gradually deteriorate. A hot coil must be located, if it exists, and be replaced. Its high temperature can be felt by the hand.

AMOUNT OF AIR GAP AND PLAY IN BEARINGS.

Since the air gap is so small in an induction motor, being from 0.015 inch in a 10-horsepower motor, to 0.06 inch in a 1,500-horsepower motor, it should be uniform throughout. The bearings should not have enough play in any direction to enable the rotor to encroach upon it seriously. The gap should, therefore, be carefully tested with the motor tipped in all four directions. The end-play should be considered, as in an alternator.

SATISFACTORY OPERATION AND STARTING.

The starting switch should be tried, if power is avail-

able, to see if any sparking occurs as the brushes pass from point to point, and also to see that no jumping of current and undue or too little acceleration occur, as the brushes pass from point to point.

The remaining items listed from 12 to 15, Chapter XII on Testing Alternating-Current Generators should be covered for motors and the discussion under those items applies to motors also.

While this list of testing data of interest to a purchaser looks long on paper, it takes only a short time to obtain it in a testing room, and the money spent is a cheap insurance of future excellence of operation under all ordinary conditions for many years.

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